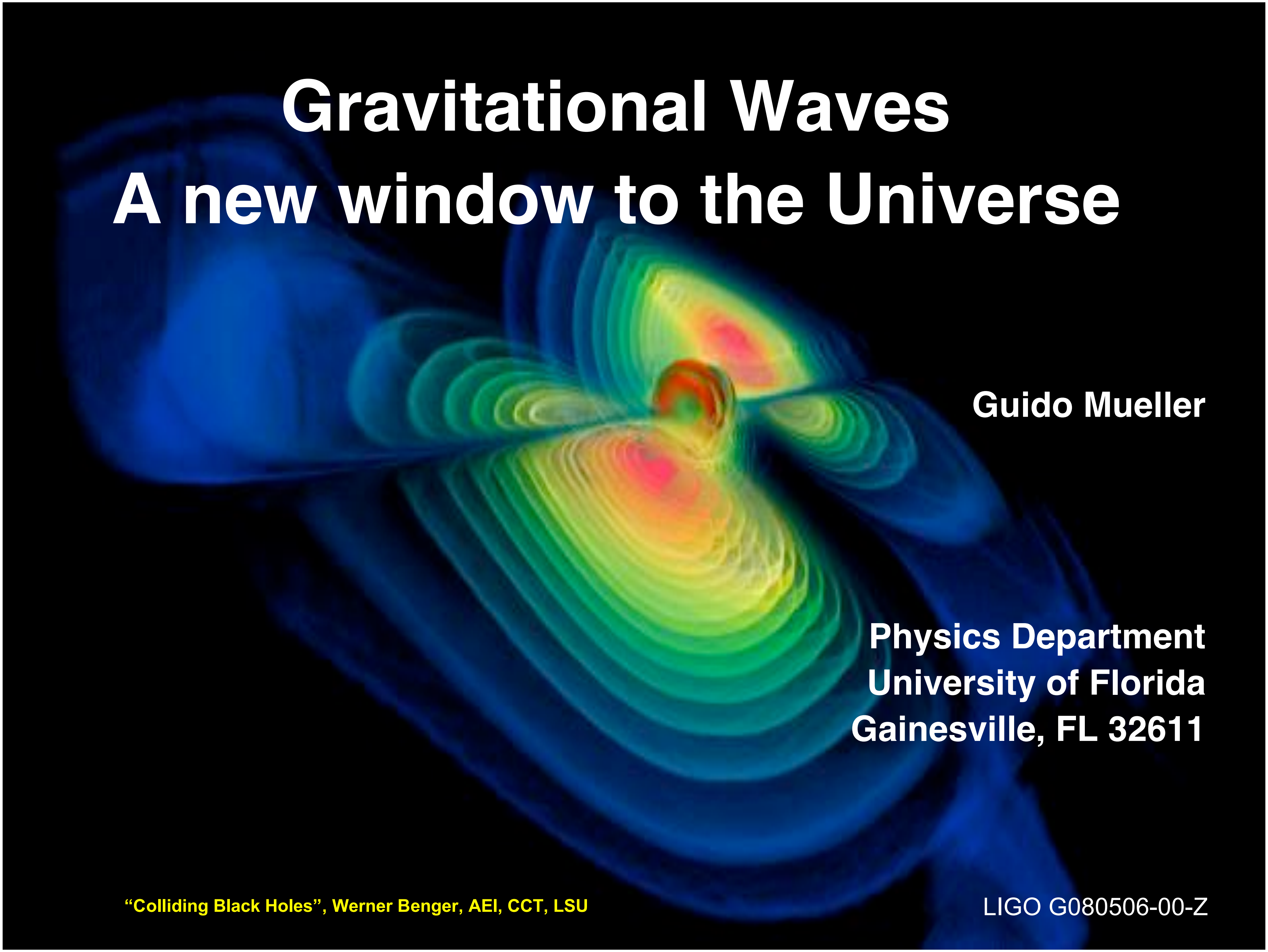
Gravitational Waves
A new window to the Universe



Guido Mueller

Physics Department
University of Florida
Gainesville, FL 32611

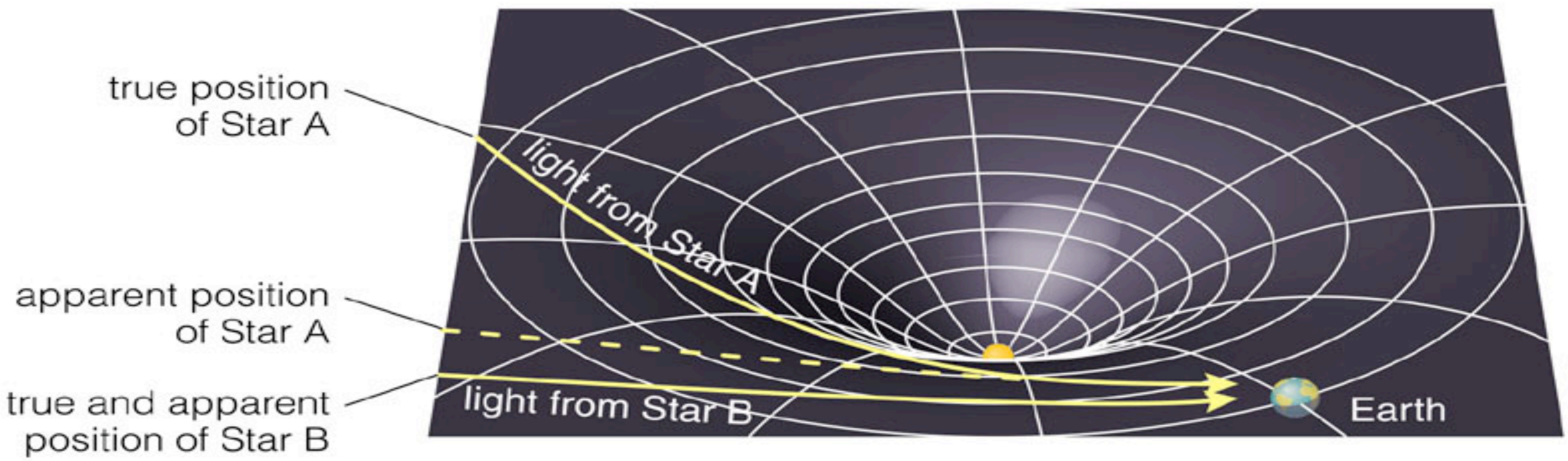
"Colliding Black Holes", Werner Benger, AEI, CCT, LSU

LIGO G080506-00-Z

Gravitational Waves
The Basics

Gravitational waves for laser physicists

- "Gravity is Geometry"
  - Space tells matter how to move ←→ matter tells space how to curve



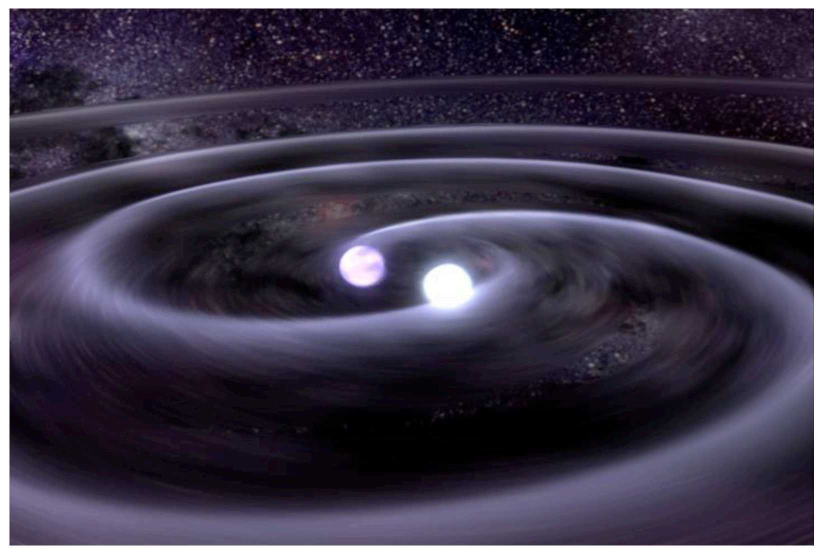
Gravitational waves for laser physicists

- "Gravity is Geometry"
  - Space tells matter how to move ←→ matter tells space how to curve
  - Two masses orbit around each other ←→ Changes curvature in space

- Propagating gravitational waves: $h_{\mu\nu}^{\mathrm{TT}}(t,z) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h = 0$$

$$h(t) \sim h_{\mu\nu}\, e^{i(\vec{k}\bullet\vec{x}\ -\omega t)} + h_{\mu\nu} e^{-i(\vec{k}\bullet\vec{x}-\omega t)}$$



Credit: Tod Strohmayer (GSFC)

Gravitational waves & electromagnetic waves: a comparison

Electromagnetic Waves

- Time-dependent dipole moment arising from *charge motion*

$$\vec{E}(\vec{r},t) \sim \frac{\mu_0}{4\pi r}\left[\hat{r}\times\left(\hat{r}\times\ddot{\vec{p}}\right)\right]$$

- Traveling wave solutions of Maxwell wave equation, $v = c$
- Two polarizations: σ^{+}, σ^{-}

Gravitational Waves

- Time-dependent quadrapole moment arising from *mass motion*

$$h_{\mu\nu}(\omega,t) = \frac{2G}{r\,c^4}\ddot{I}_{\mu\nu}(\omega,t)$$

$$\boxed{h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{r c^4}}$$

- Traveling wave solutions of Einstein's equation, $v = c$
- Two polarizations: h_+, h_x

Energy in Gravitational Waves

NS/NS merger (M$_{NS}$ ~ 3x10^{30}kg ~ 1.4 M$_{Sun}$)

1. Smallest Distance: d_{min} ~ 20km (2xDiameter of NS)
2. Potential Energy: E = - GM^2/d ~ 3x10^{46}J
3. Newton: f (d=100km) ~ 100 Hz, f (d=20km) ~ 1 kHz
4. Takes a couple 10 sec to get from 100km to 20km
5. During this time nearly half of the Potential Energy is radiated away!
6. Assume binary is in the Virgo cluster (15 Mpc ~ 6x10^{24} m)

Energy in Gravitational Waves

NS/NS merger $(M_{NS} \sim 3 \times 10^{30} kg \sim 1.4\ M_{Sun})$

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4. Takes a couple 10 sec to get from 100km to 20km
5. During this time nearly half of the Potential Energy is radiated away!
6. Assume binary is in the Virgo cluster (15 Mpc ~ 6×10^{24} m)

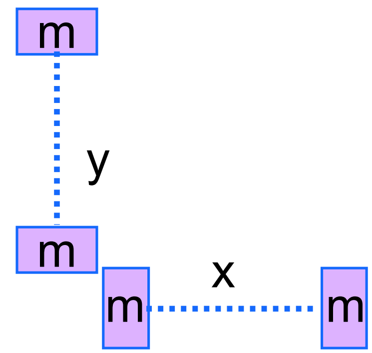
We receive about $P = 1..100 mW/m^2$ from each binary! Like full moon during a clear night!

Gravitational Waves

We can see the moon, why haven't we seen Gravitational Waves yet?

Gravitational Waves

- Effect of a gravitational wave (in z) on light traveling between <u>freely falling masses</u>, observer fixed to near masses



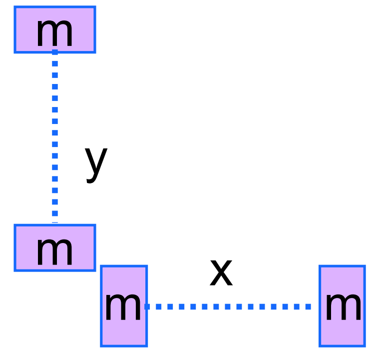
$$ds^2 \equiv 0 = -c^2dt^2 + (1+h_+)dx^2 + (1-h_+)dy^2 \qquad |h_+| << 1$$

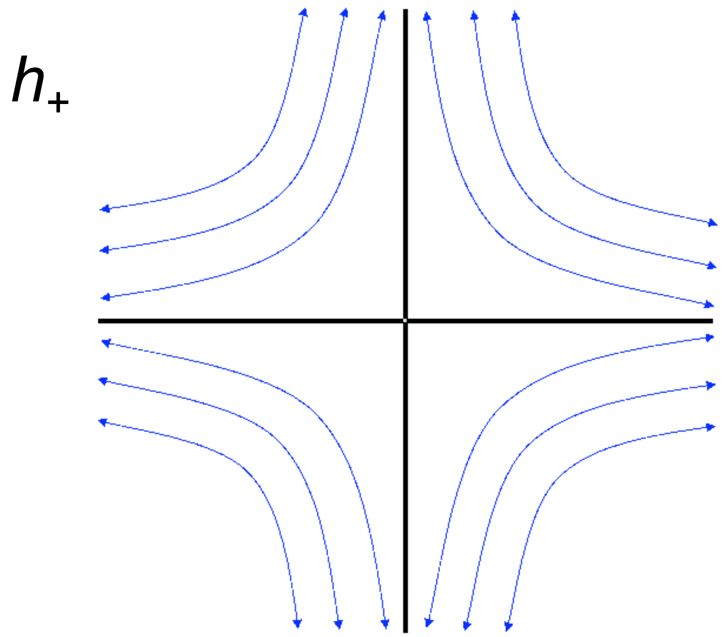
$$\Rightarrow \quad \Delta T_{rt} = \frac{2}{c}\left[\int_0^L \sqrt{1+h_+}\,dx - \int_0^L \sqrt{1-h_+}\,dy\right] \approx \frac{2h_+}{c}L$$

$$\Rightarrow \quad \Delta L = c\Delta T_{rt} = h_+ L \quad \Rightarrow \quad h_+ = \Delta L / L$$

Gravitational Wave for Laser Physicists

- Effect of a gravitational wave (in z) on light traveling between <u>freely falling masses</u>, observer fixed to near masses

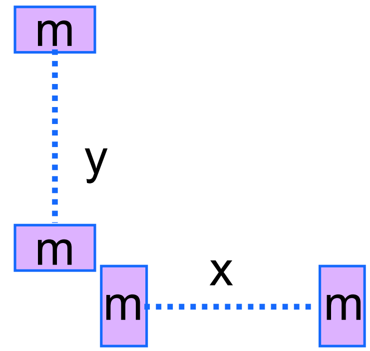




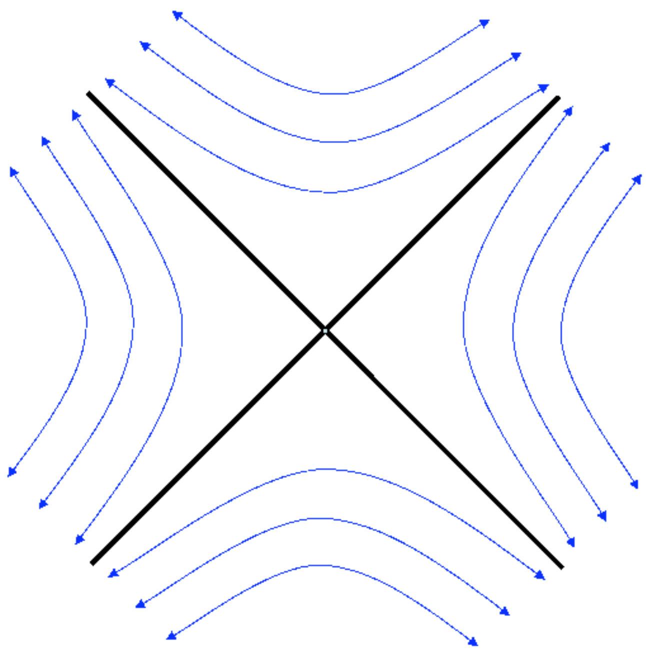
h is a *strain*: $\Delta L/L$

Gravitational Wave for Laser Physicists

- Effect of a gravitational wave (in z) on light traveling between <u>freely falling masses</u>, observer fixed to near masses

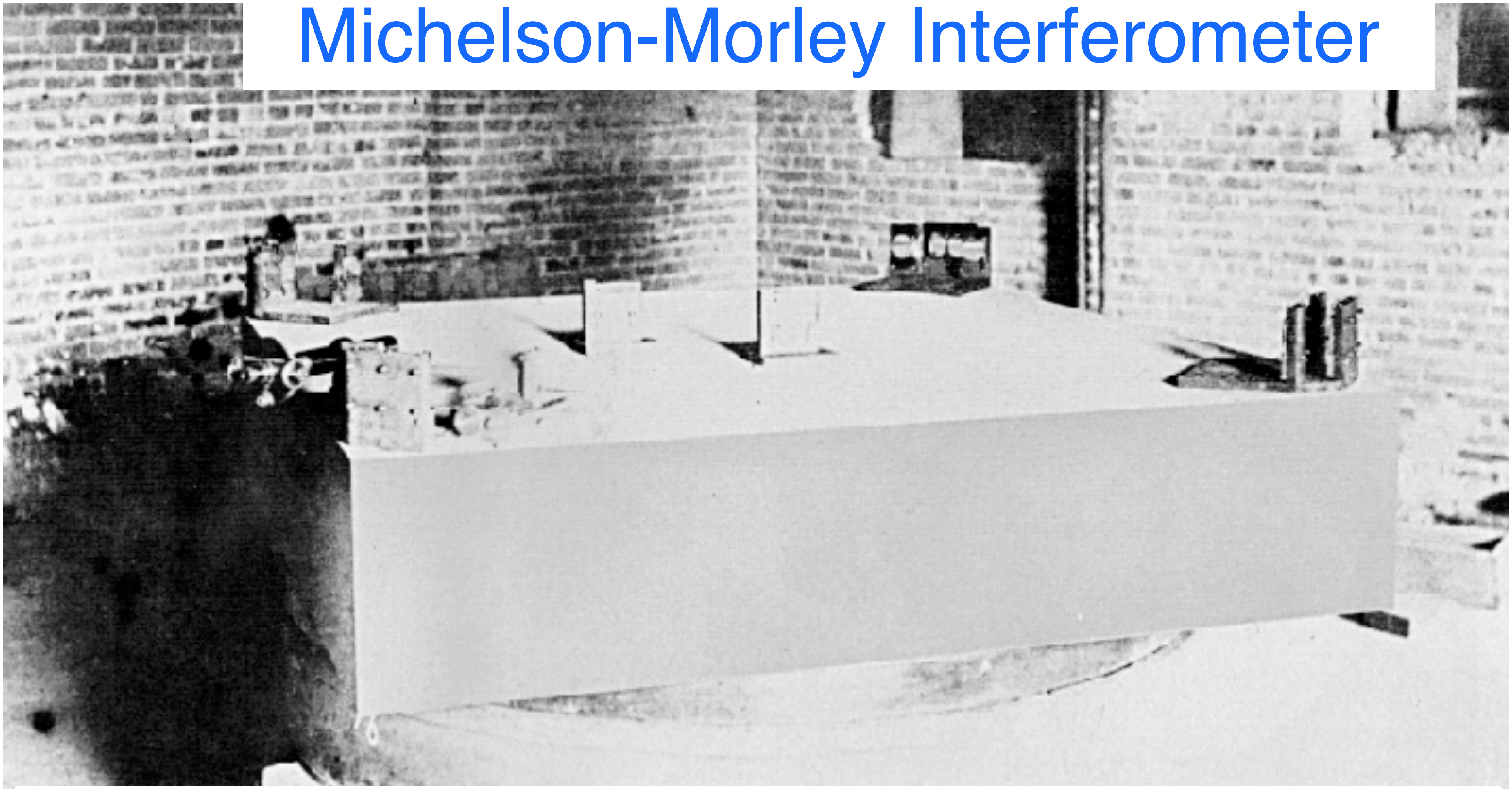


h_x

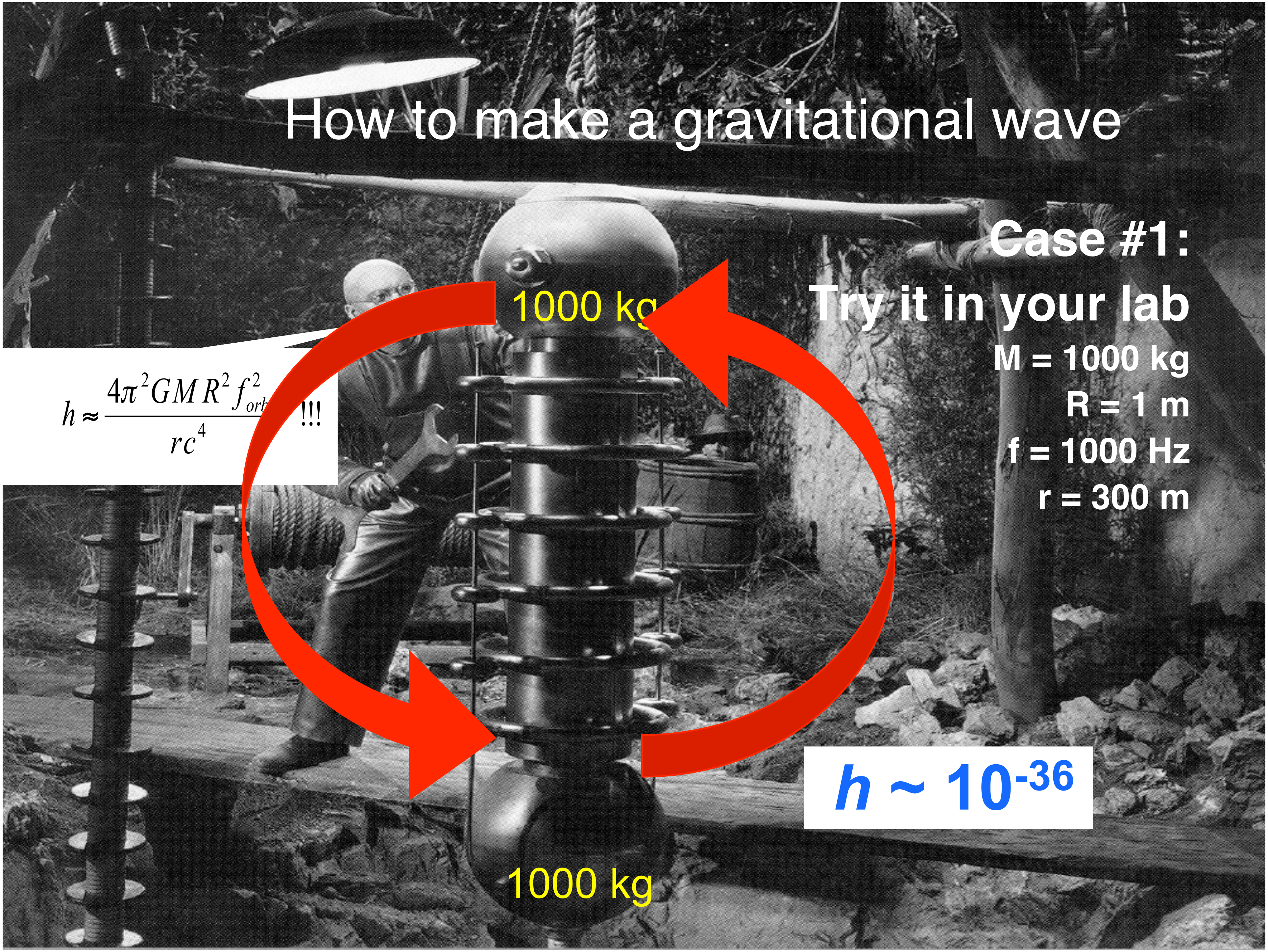


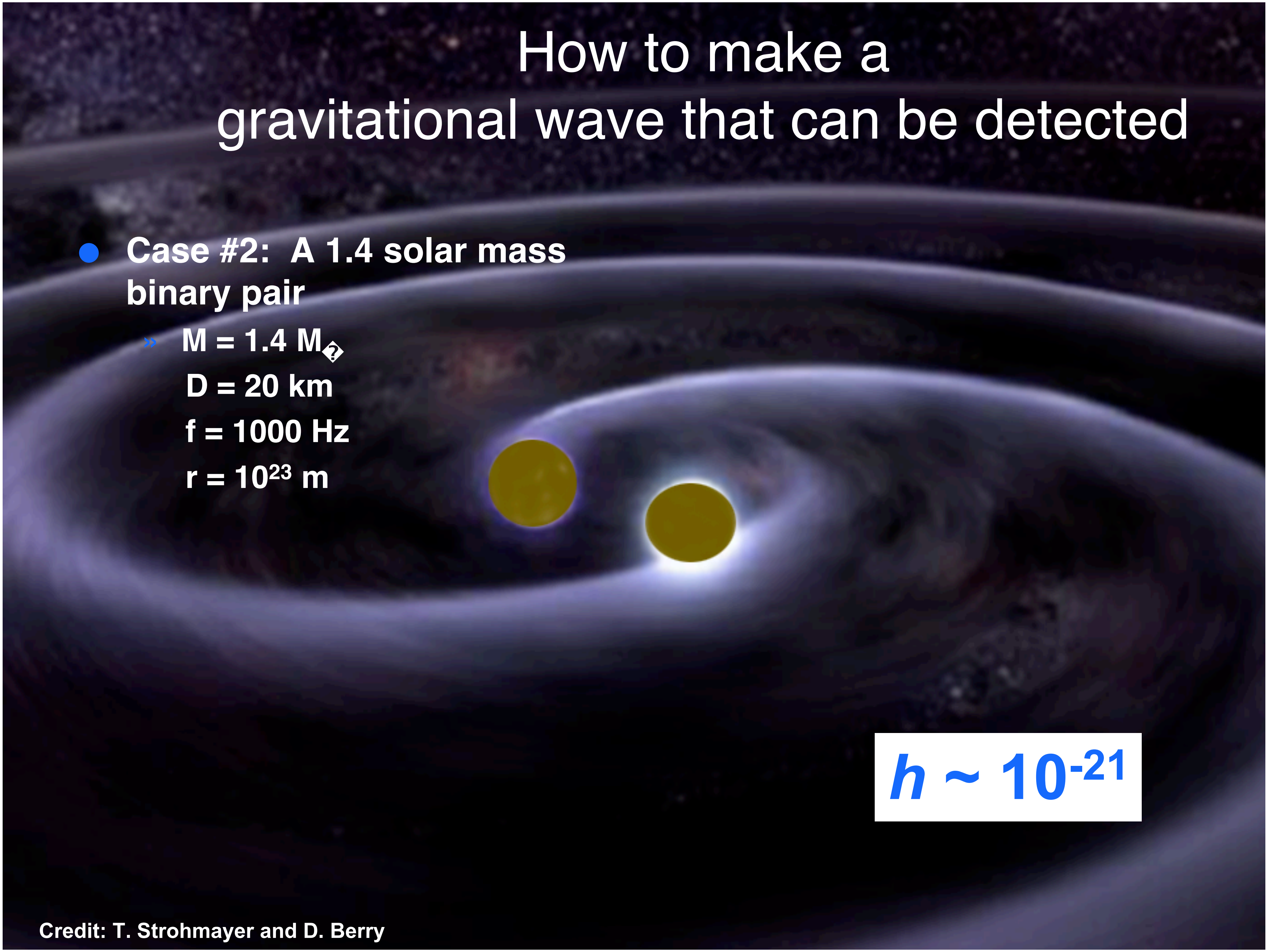
***h* is a *strain*: ΔL/L**

Michelson-Morley Interferometer



ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*


How to make a gravitational wave
Case #1:
Try it in your lab
M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m
1000 kg
1000 kg
$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{r c^4}$!!!
$h \sim 10^{-36}$


How to make a gravitational wave that can be detected
Case #2: A 1.4 solar mass binary pair
$M = 1.4\ M_{\odot}$
$D = 20$ km
$f = 1000$ Hz
$r = 10^{23}$ m
$h \sim 10^{-21}$
Credit: T. Strohmayer and D. Berry

Gravitational Waves

We can see the moon, why haven't we seen Gravitational Waves yet?

$$G/c^4 = 10^{-45} s^2/kg\ m$$

Answer: Space is stiff

LIGO

The ground-based Detector

How to detect a gravitational wave

Rai Weiss, MIT

Ron Drever, Caltech

1972!

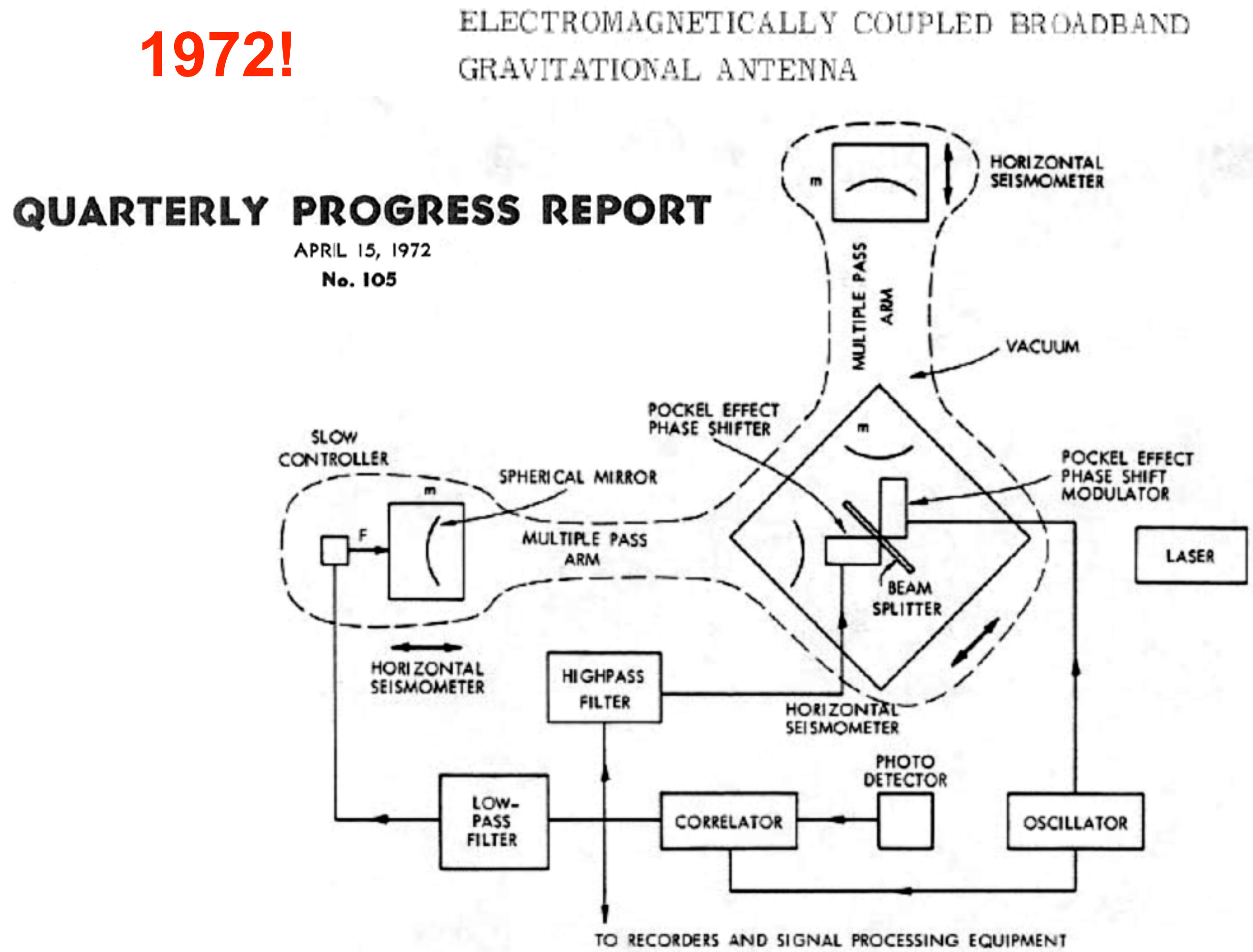
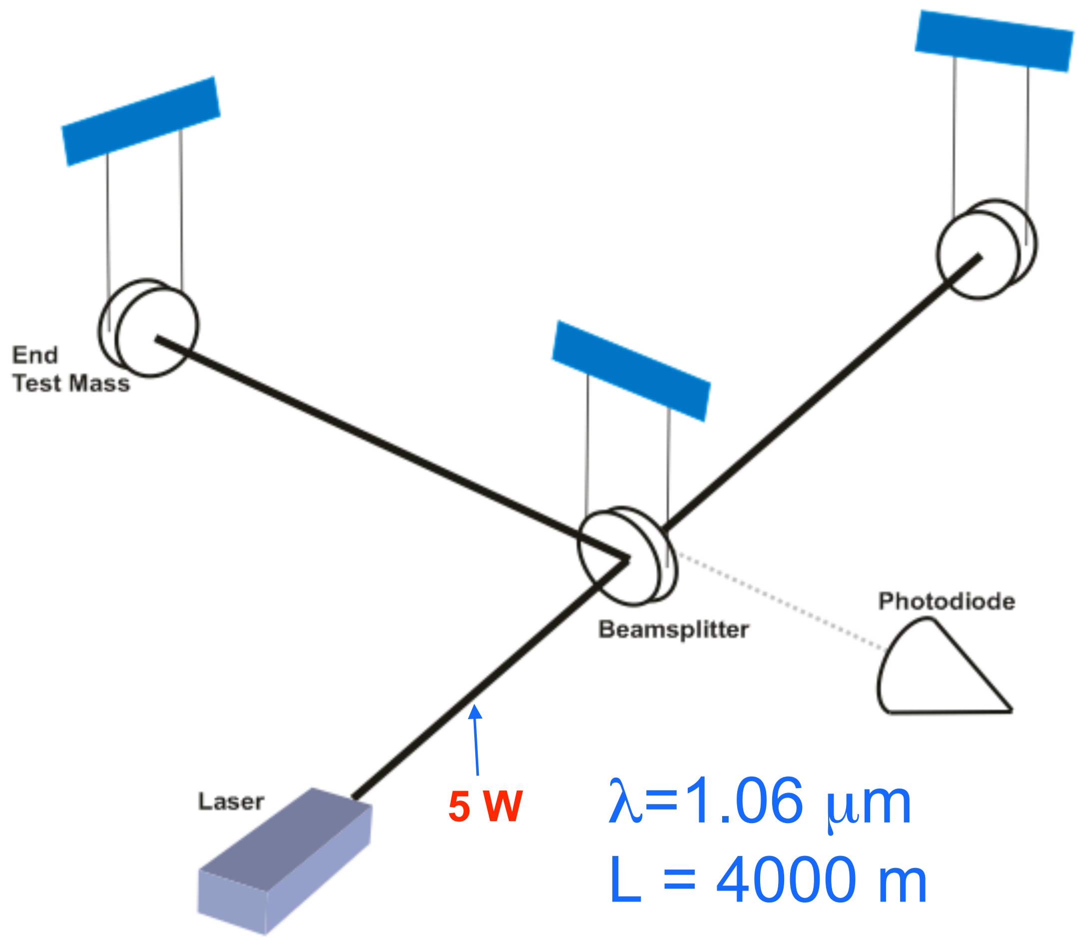


Fig. V-20. Proposed antenna.

Realistically, how sensitive can an interferometer be?

$$h \sim \frac{\lambda}{L}$$

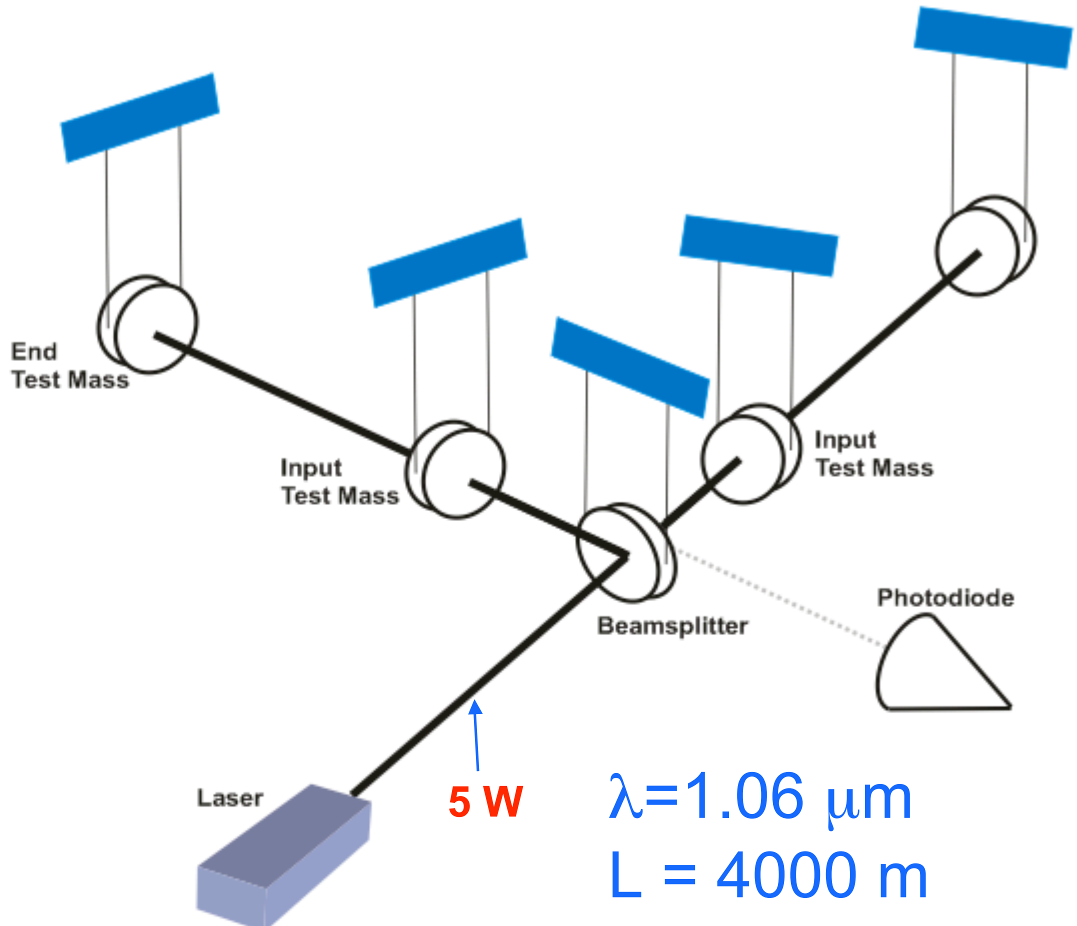


λ=1.06 μm
L = 4000 m

Realistically, how sensitive can an interferometer be?

$$h \sim \frac{\lambda}{L}$$

$$\times \frac{1}{N_{roundtrip}}$$



λ=1.06 μm

L = 4000 m

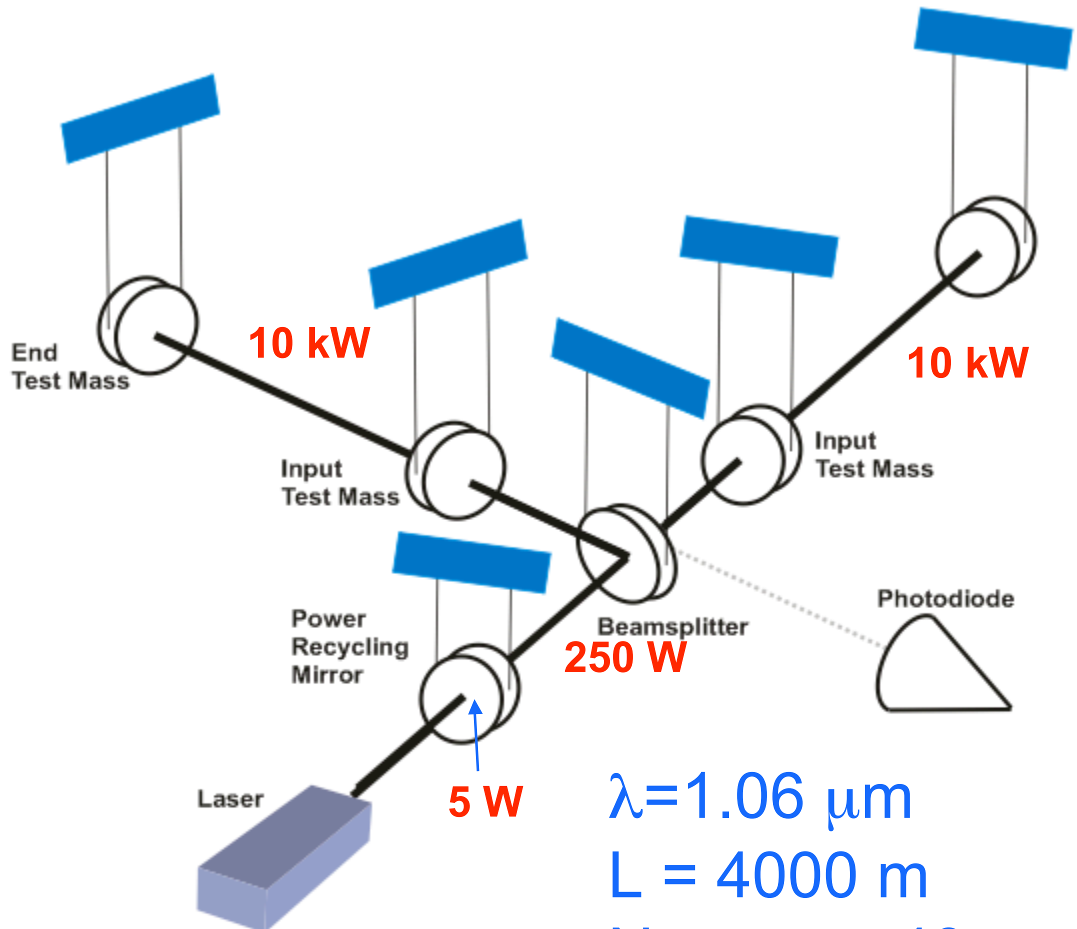
$N_{roundtrip}$ = 40

Realistically, how sensitive can an interferometer be?

$$h \sim \frac{\lambda}{L}$$

$$\times \frac{1}{N_{roundtrip}}$$

$$\times \sqrt{\frac{1}{\dot{N}_{photon} T_{meas}}}$$



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Realistically, how sensitive can an interferometer be?

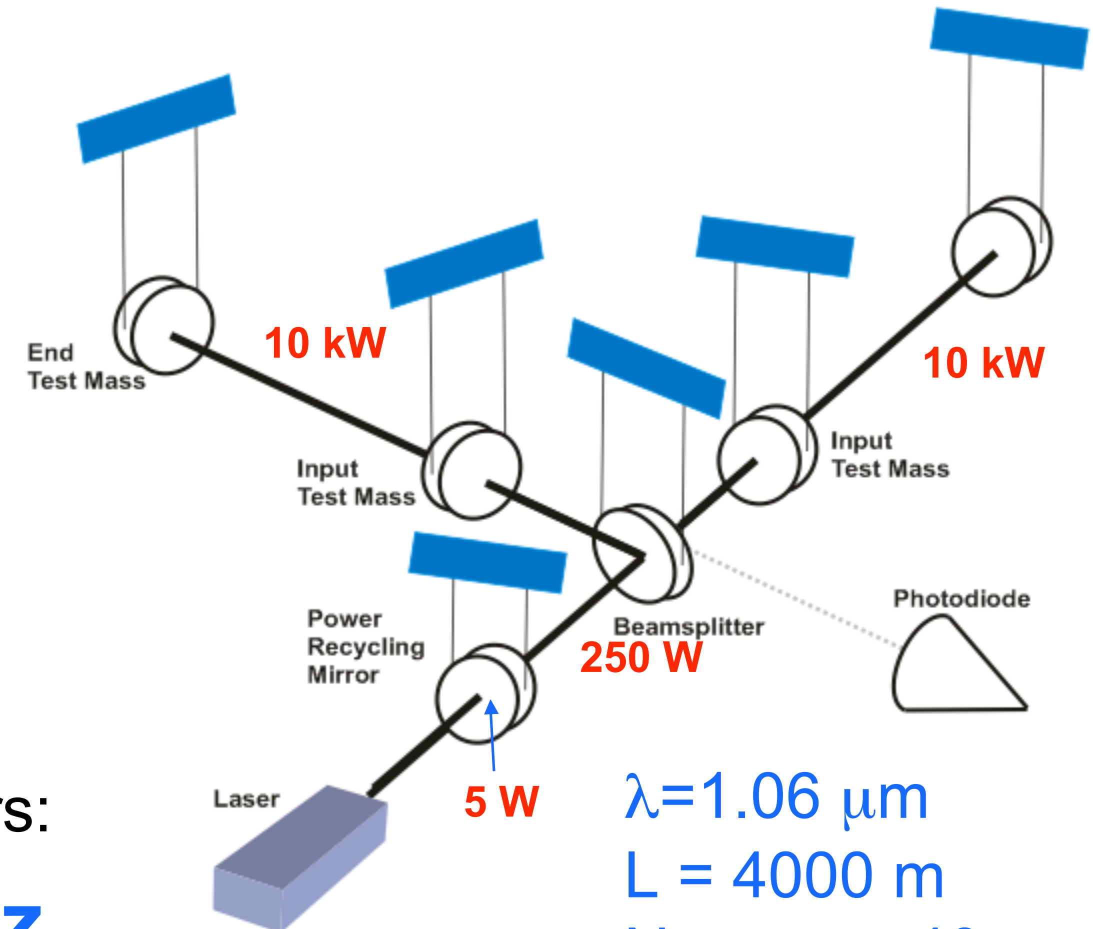
$$h \sim \frac{\lambda}{L}$$

$$\times \; \frac{1}{N_{roundtrip}}$$

$$\times \; \sqrt{\frac{1}{\dot{N}_{photon} T_{meas}}}$$

Putting in numbers:

***h* ~ 10^{-21}/rtHz**



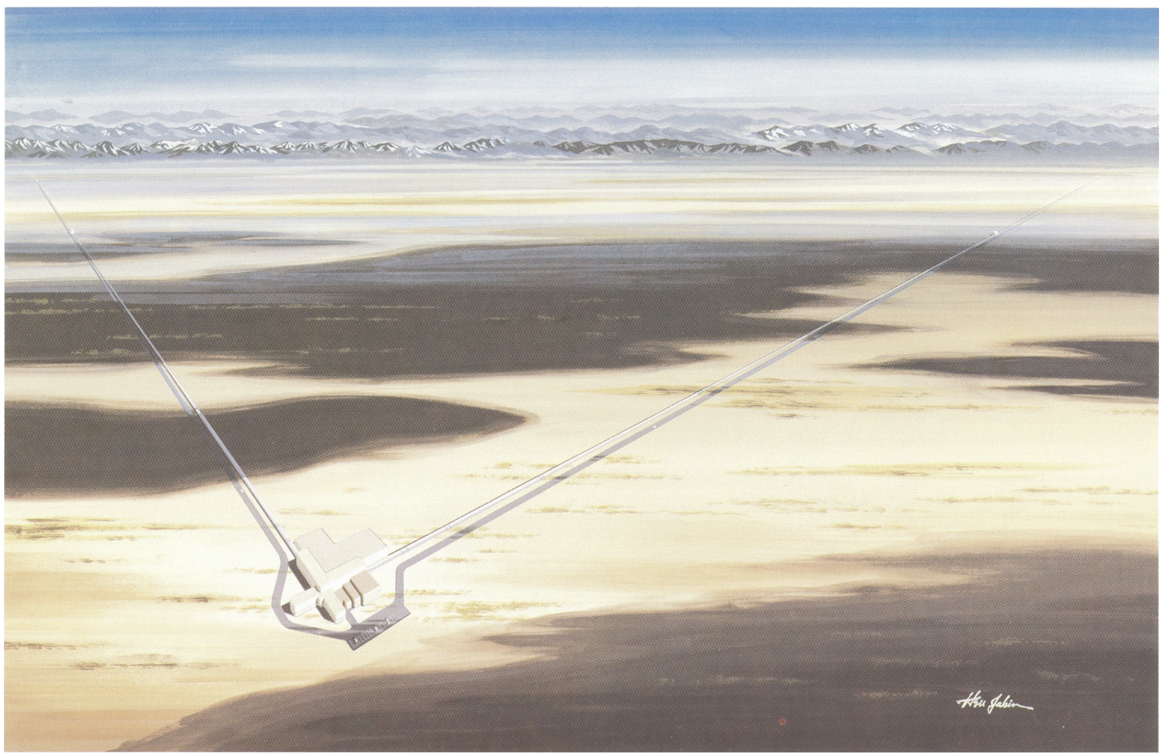
λ=1.06 μm
L = 4000 m
$N_{roundtrip}$ = 40

1989 Proposal to the US NSF

PREFACE

This proposal requests support for the design and construction of a novel scientific facility—a gravitational-wave observatory—that will open a new observational window on the universe.

The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.




Hanford,
Washington

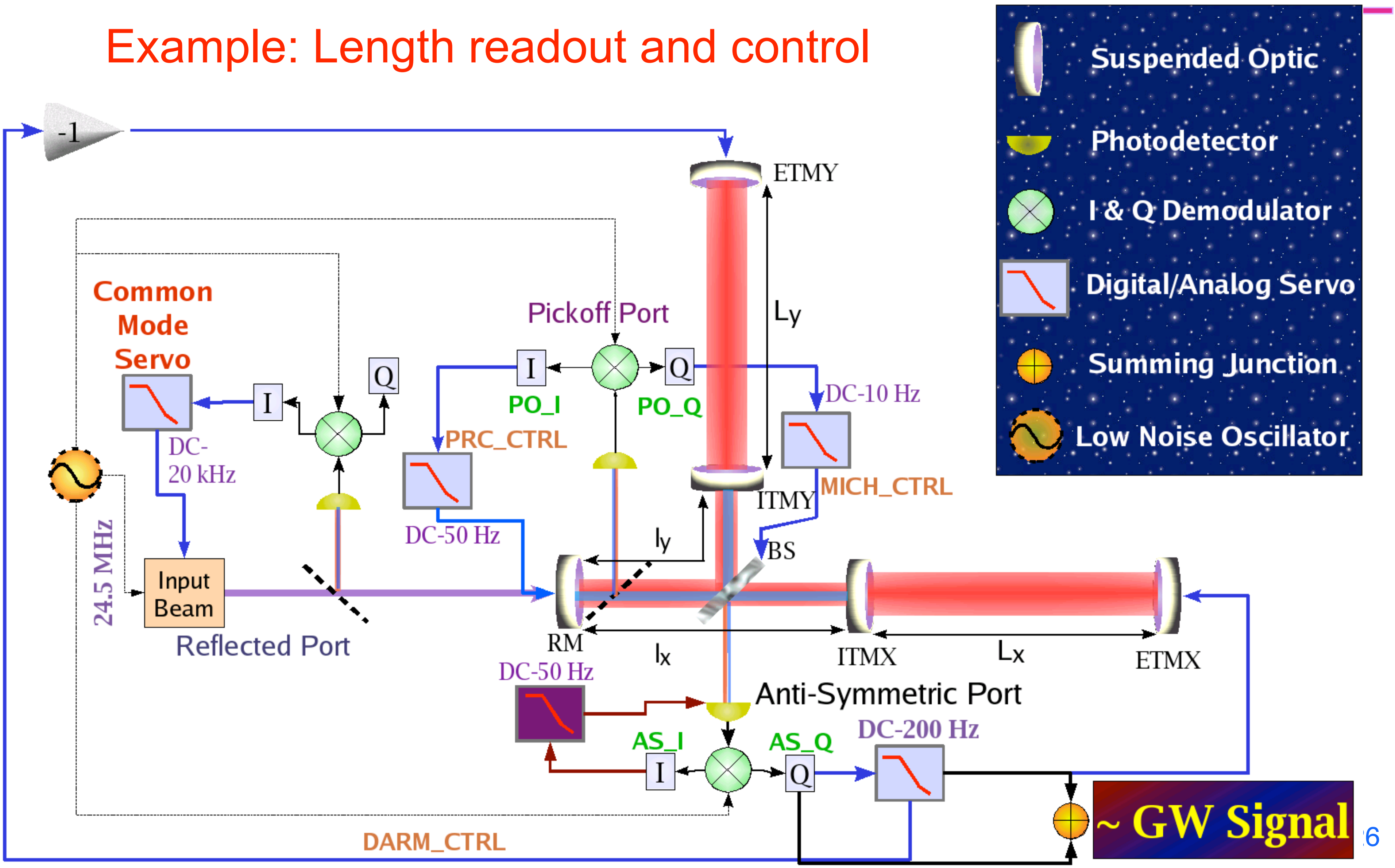

Livingston,
Louisiana

LIGO

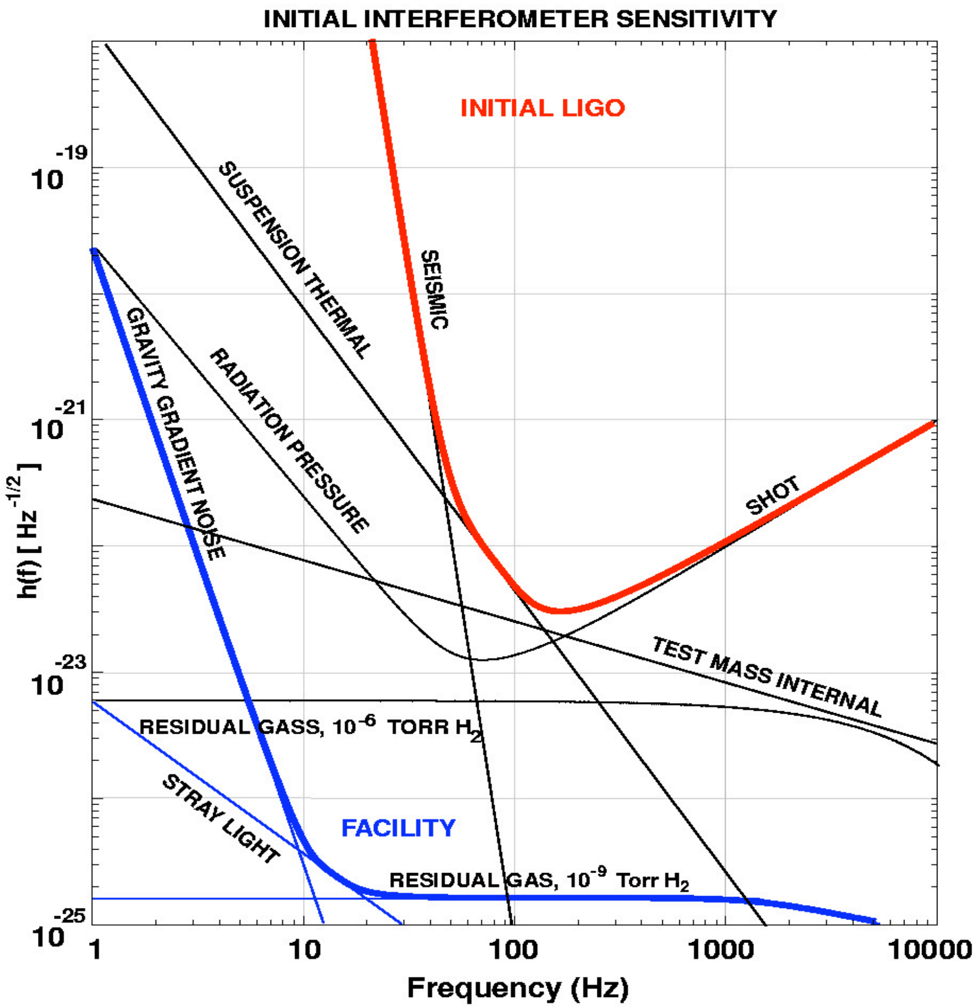
How does it work?

How does LIGO work?
LIGO is a gigantic control problem

Example: Length readout and control

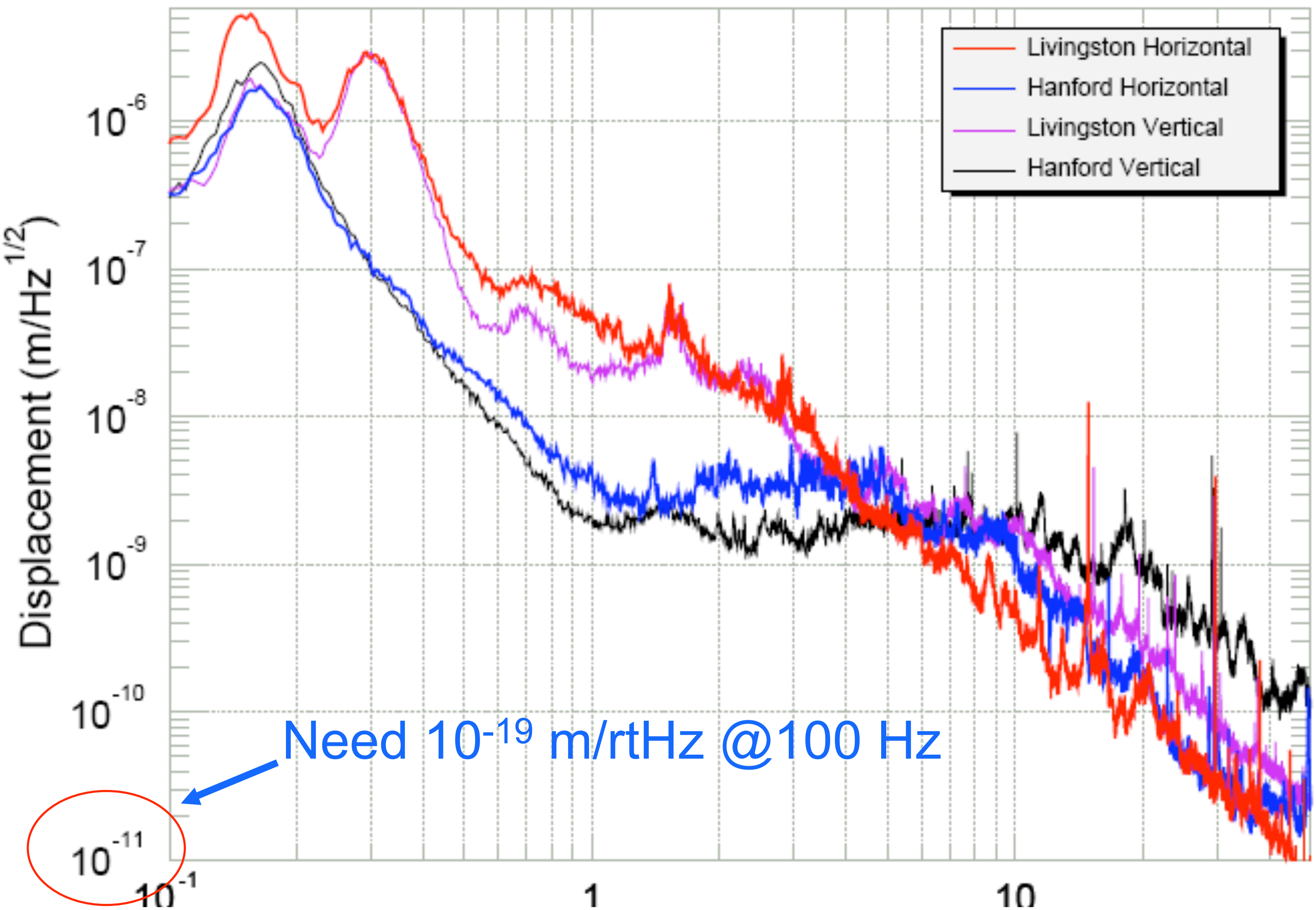


LIGO is a gigantic noise problem

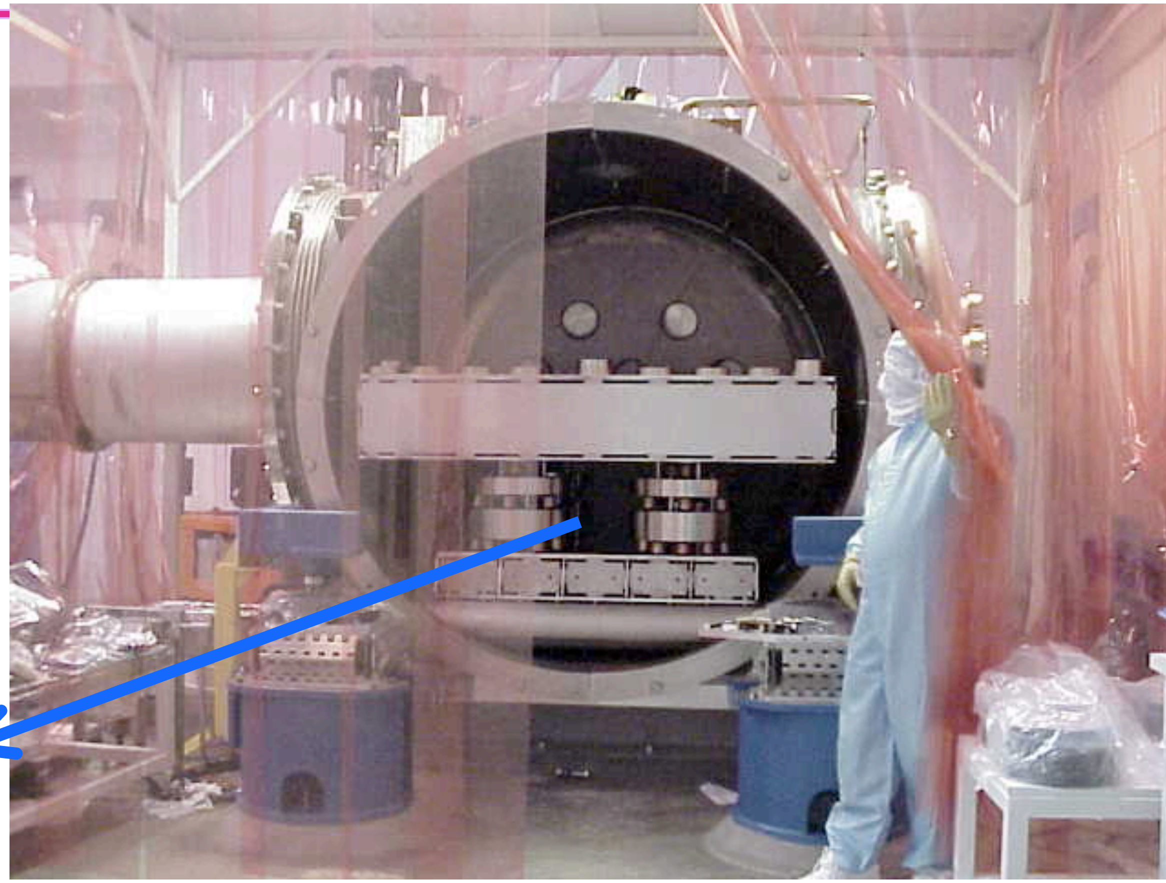


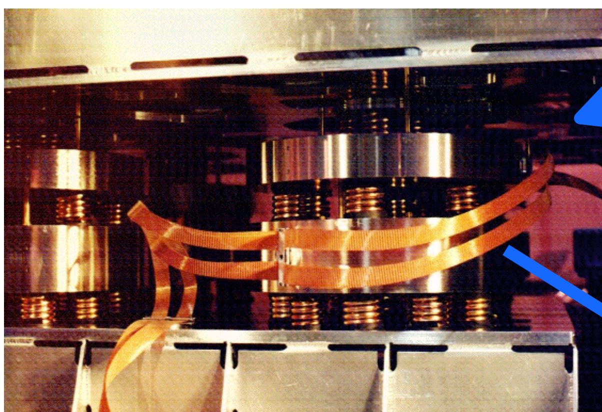
- Displacement noises
  - Seismic noise
  - Radiation pressure
  - Thermal noise
    - Suspensions
    - Optics
- Sensing noises
  - Shot noise
  - Residual gas noise

Seismic noise



Seismic noise

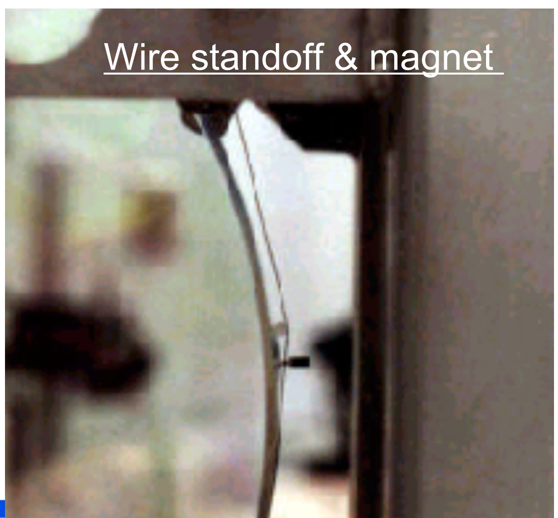


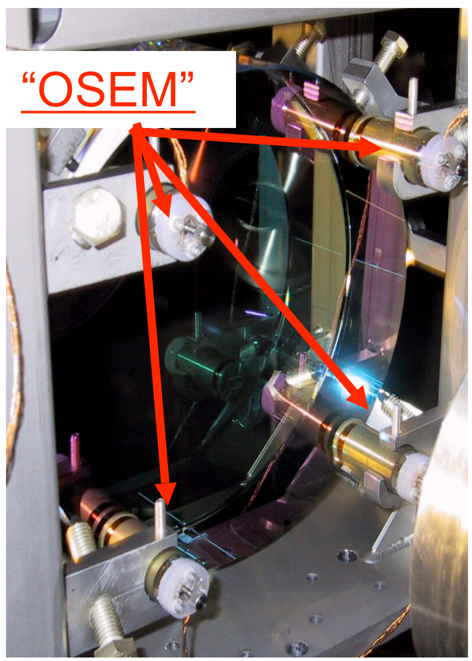


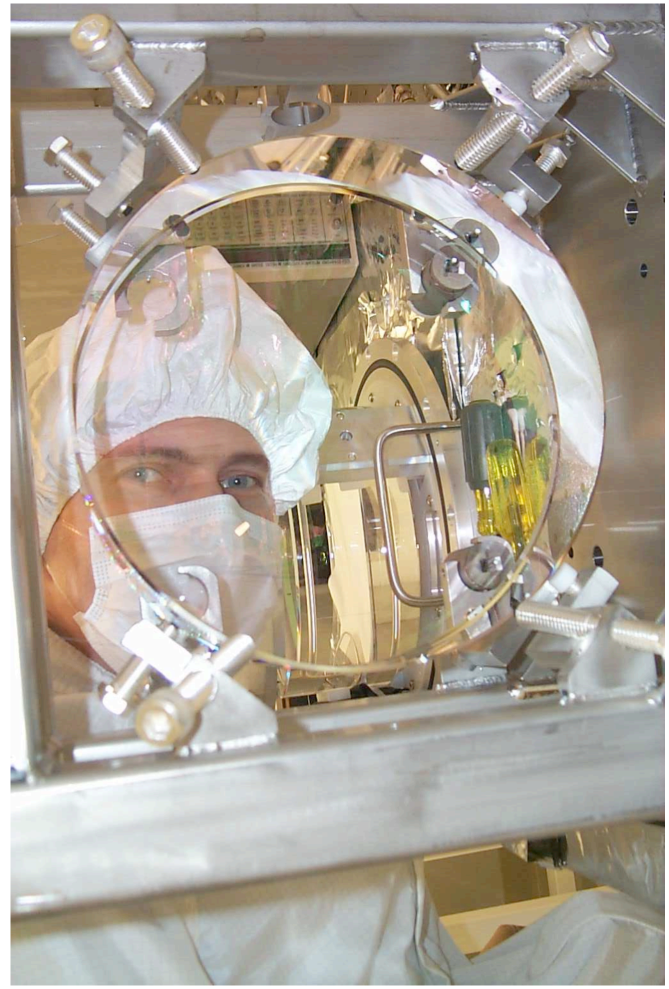
Tubular coil springs with internal damping, layered between steel reaction masses

Suspended Mirrors

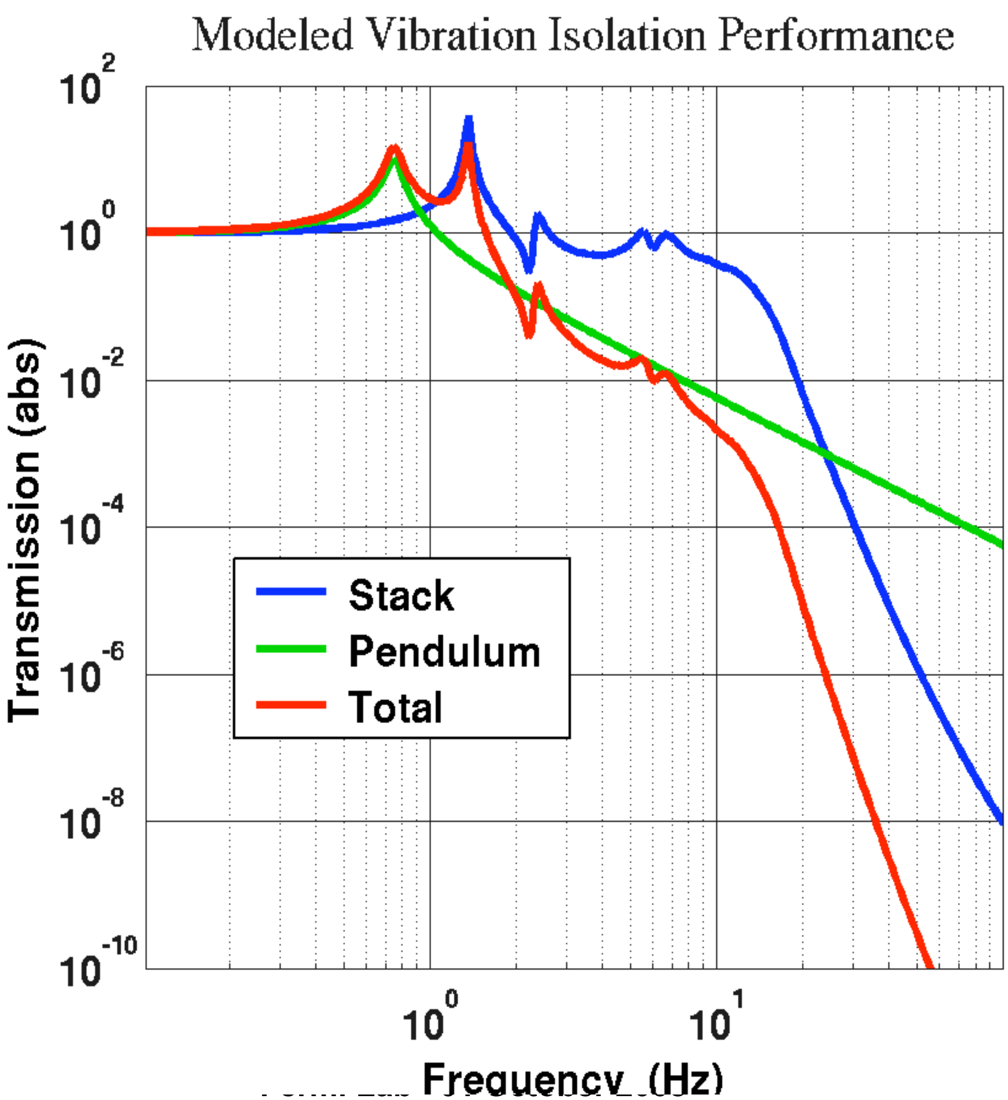
- mirrors are hung in a pendulum
  → ‘freely falling masses’
- provide $1/f^2$ suppression above 1 Hz
- provide ultra-precise control of mirror displacement (< 1 pm)



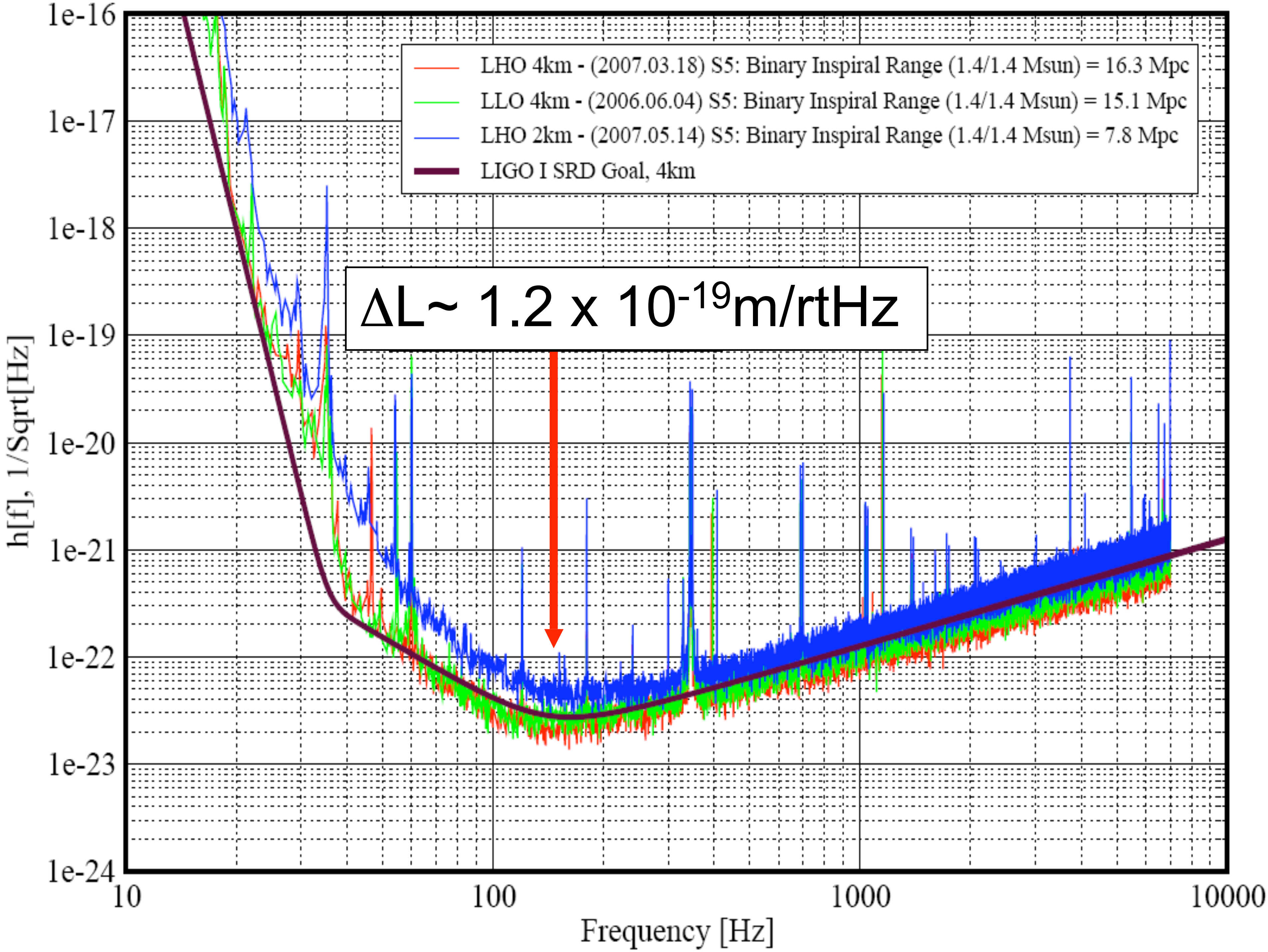




Suspended Mirrors

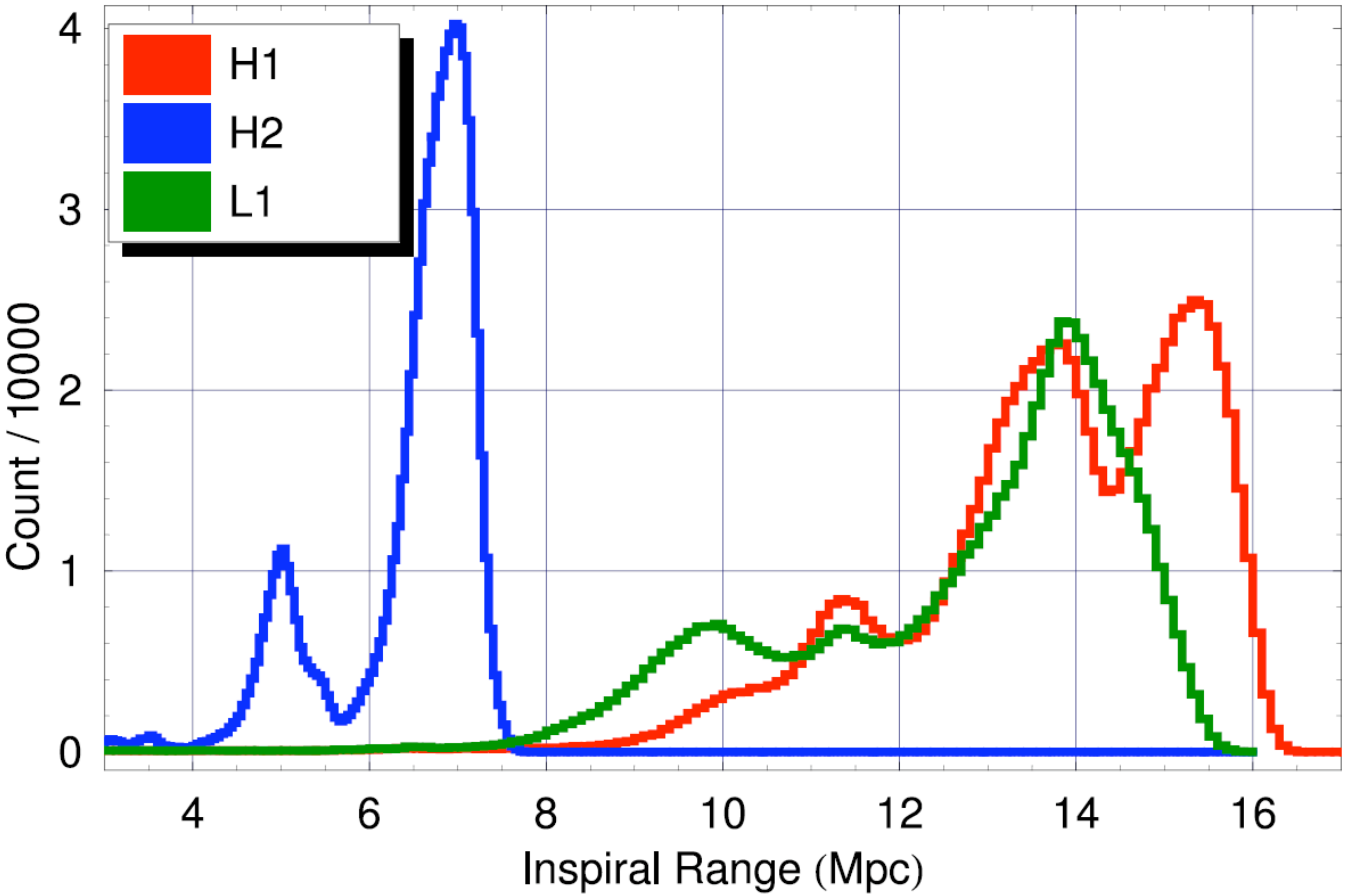


LIGO Vacuum Chambers



LHO 4km - (2007.03.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 16.3 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2007.05.14) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.8 Mpc
LIGO I SRD Goal, 4km
ΔL~ 1.2 x 10^-19 m/rtHz
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

Inspiral range during S5

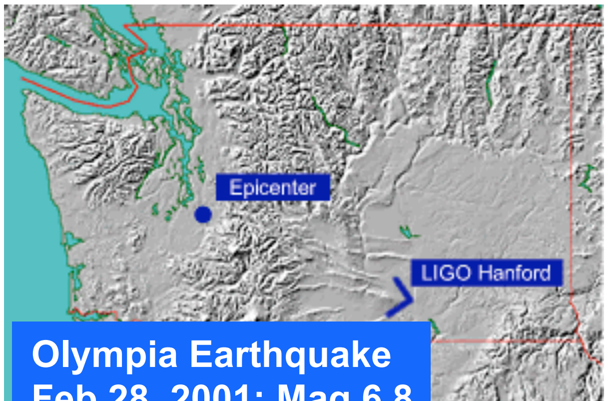


LIGO

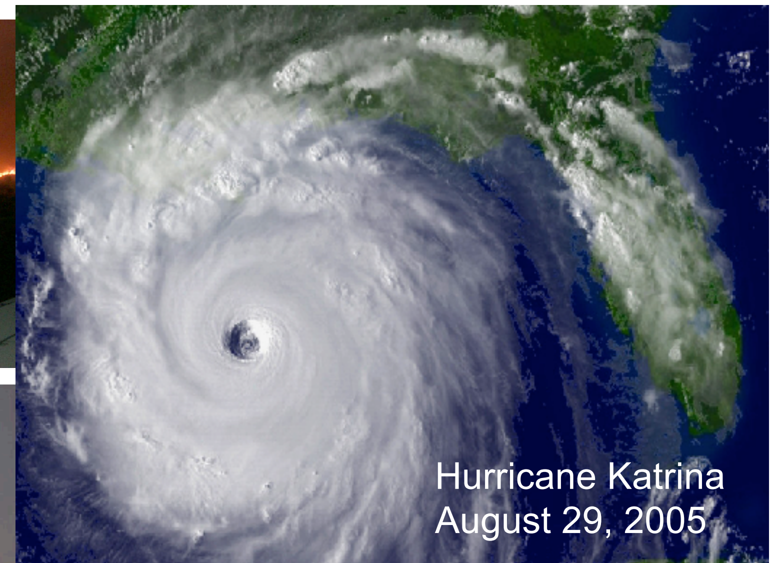
The other type

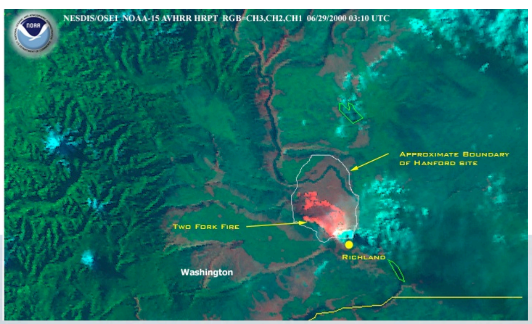
of problems

Nature can be a problem…



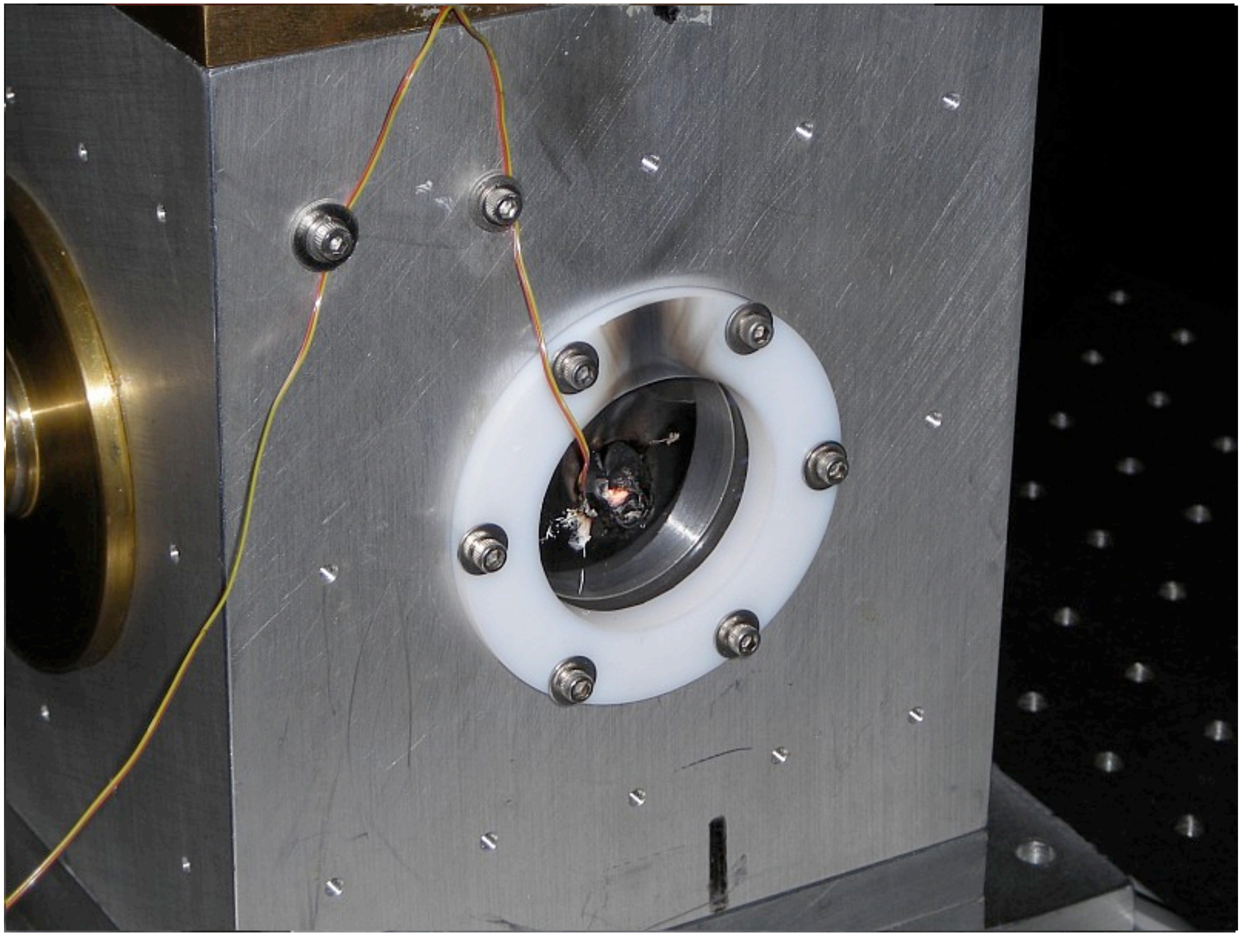
Olympia Earthquake
Feb 28, 2001; Mag 6.8


Hurricane Katrina
August 29, 2005



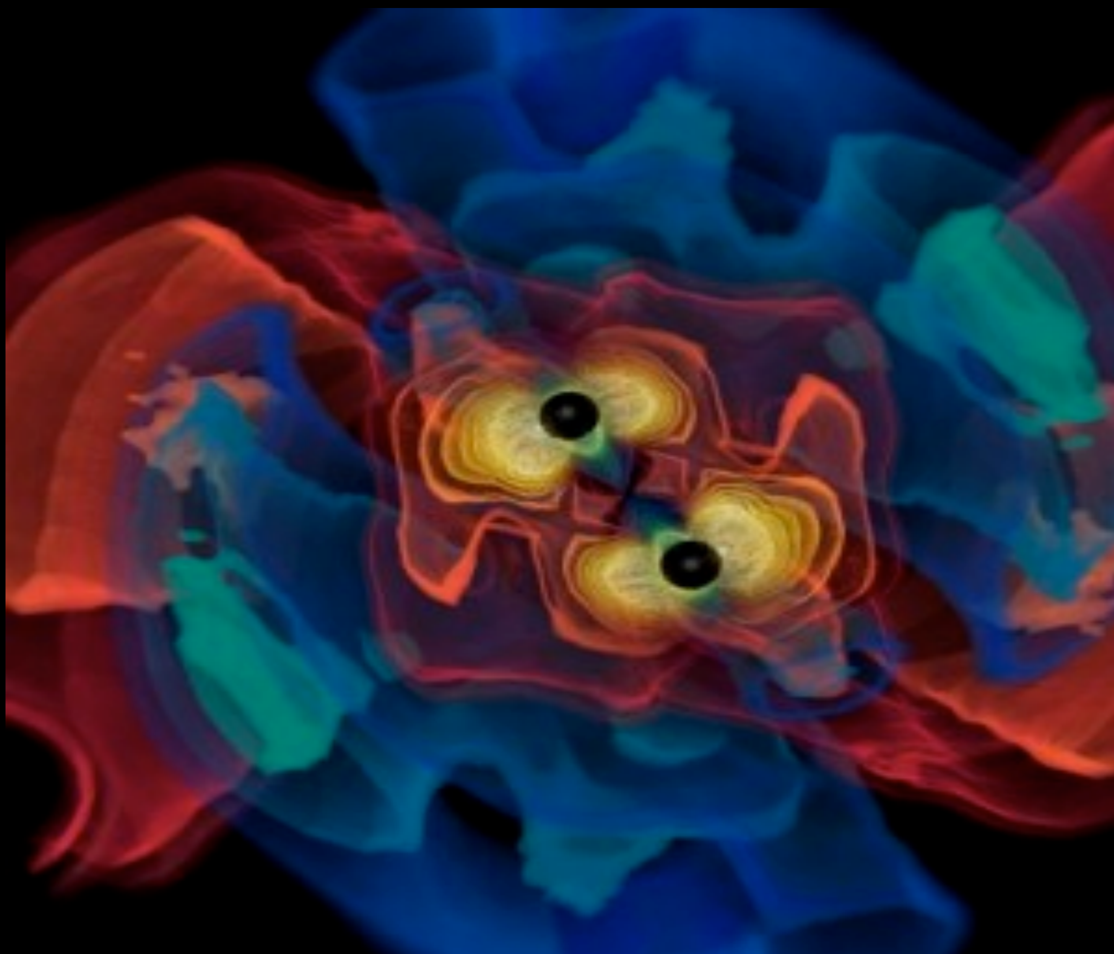
As can cars…

And bugs…



LIGO
The Sources

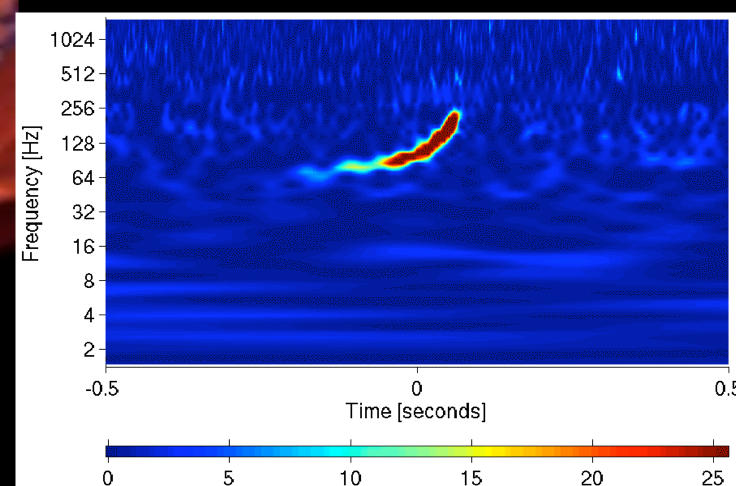
The astrophysical gravitational wave source catalog



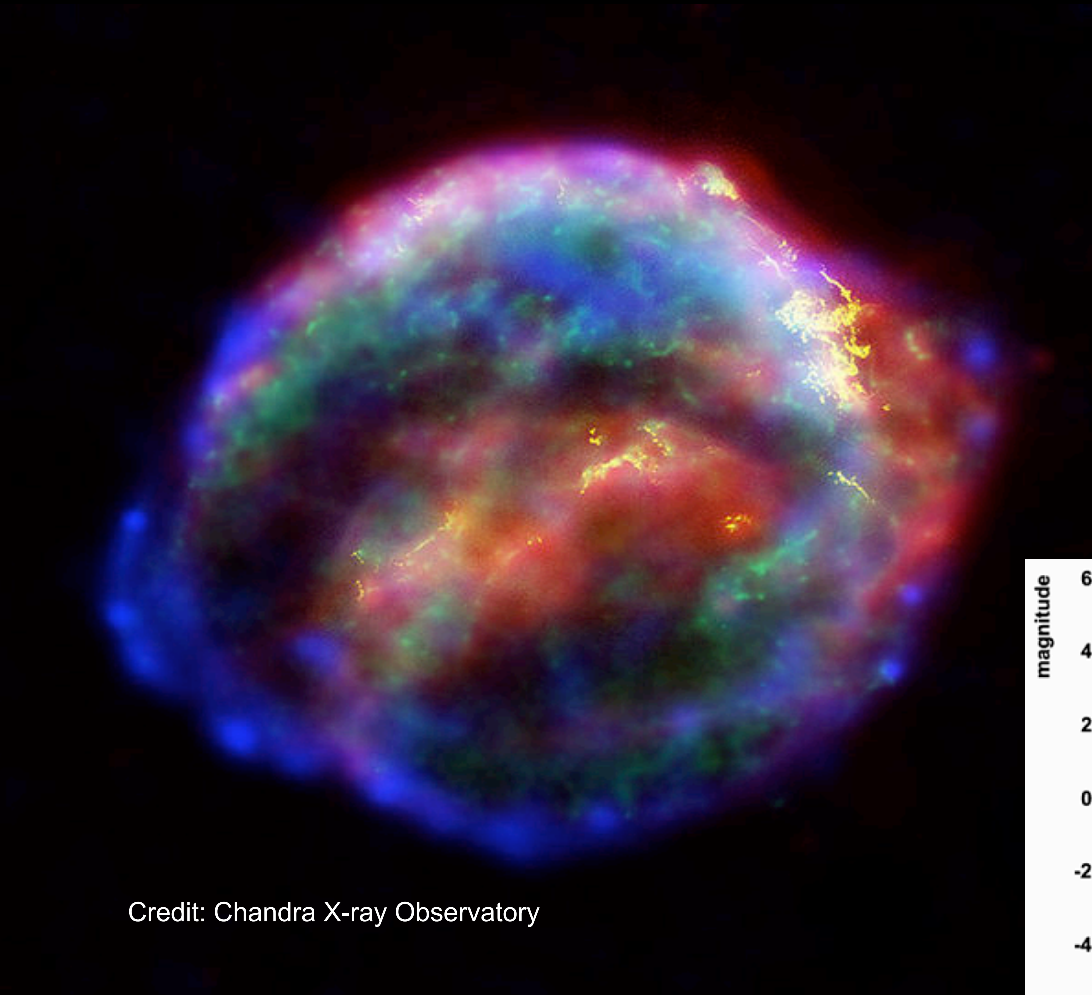
Credit: AEI, CCT, LSU

Coalescing Binary Systems

- Neutron stars, black holes
- ‘chirped’ waveform



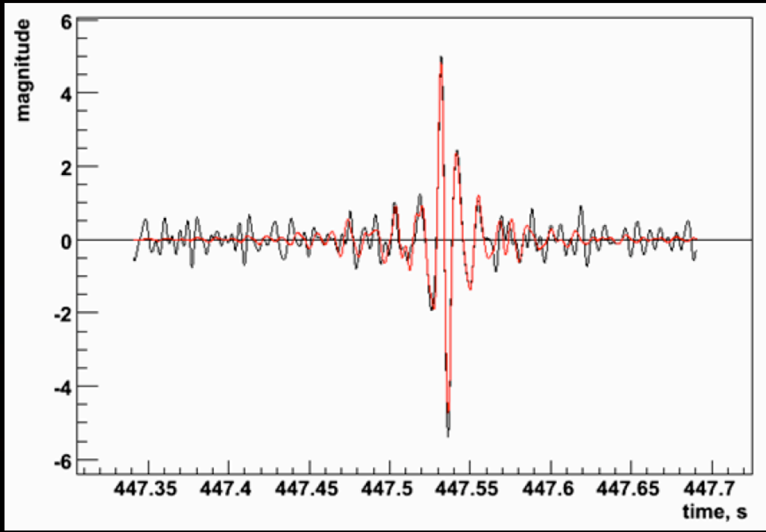
The astrophysical gravitational wave source catalog



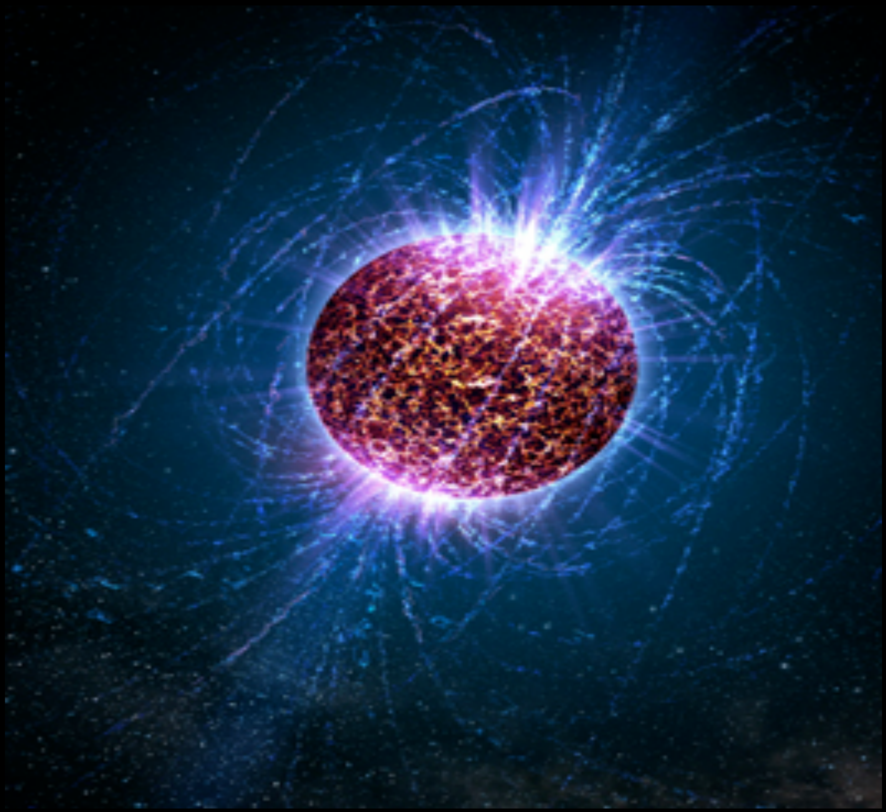
Credit: Chandra X-ray Observatory

'Bursts'

- asymmetric core collapse supernovae
- cosmic strings
- ???? (sources we haven't thought about)



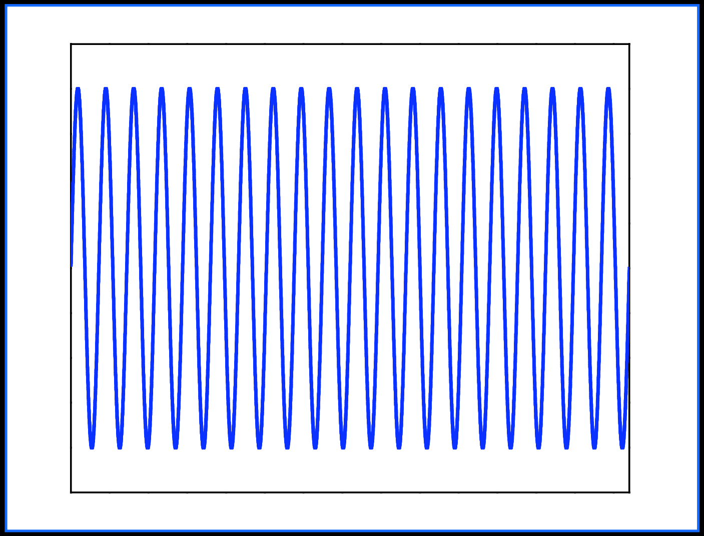
The astrophysical gravitational wave source catalog



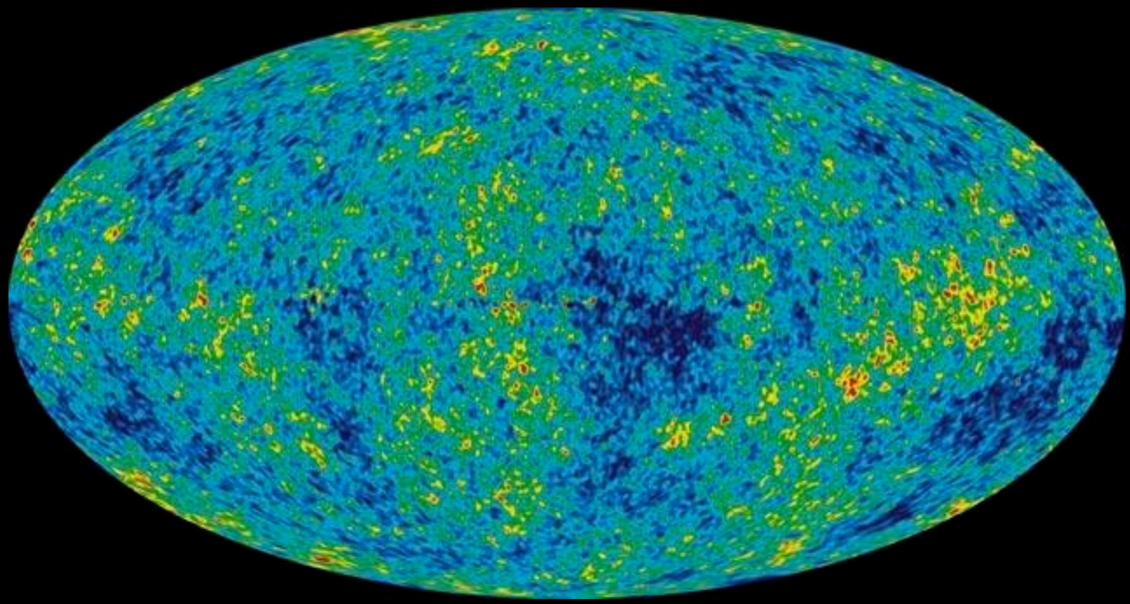
Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform



The astrophysical gravitational wave source catalog



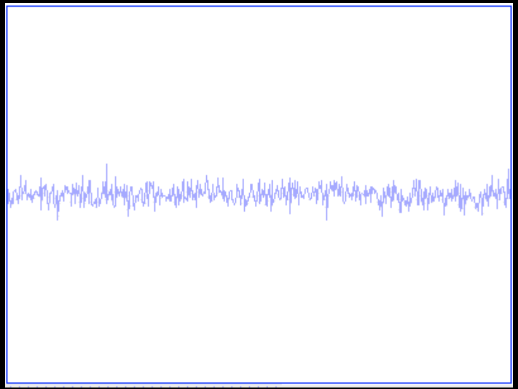
NASA/WMAP Science Team

Cosmic GW background

• residue of the Big Bang

•probes back to 10^{-21} s after the birth of the universe

• stochastic, incoherent background



LIGO
The Science
(so far)

LIGO Astrophysics

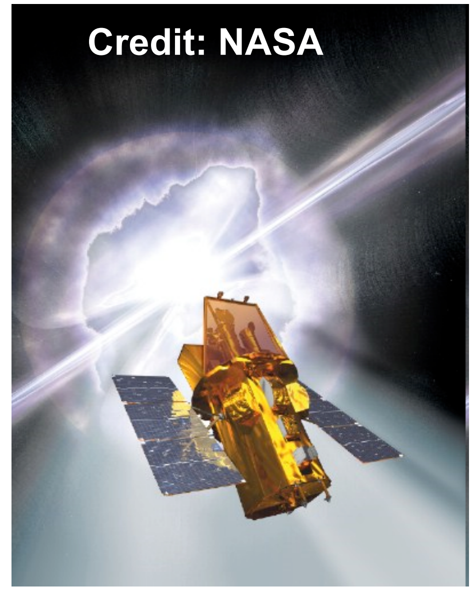
- The LIGO Scientific Collaboration
  - » 640 members, 50 institutions, 11 countries
- Five Science Runs To Date
  - » S1: August 23 - September 9, 2002 (17 days)
  - » S2: February 14 – April 14, 2003 (59 days)
  - » S3: October 31, 2003 – January 9, 2004 (70 days)
  - » S4: February 22 – March 23, 2005 (30 days)
  - » **S5: November 4, 2005 – September 31, 2007**
    - – > 365 days of triple coincidence, 400 days of double coincidence
    - – Duty cycle: 78% for the Hanford 4k, 79% for the Hanford 2k and 66% for Livingston 4k
- LSC-Virgo started data-sharing on May 18, 2007
  - » Virgo VSR1: May 18, 2007 – Oct 1, 2007
  - » >75 days of 3-site coincidences with LIGO, 95 days of 2-site coincidences
  - » Duty cycle: 81% for Virgo

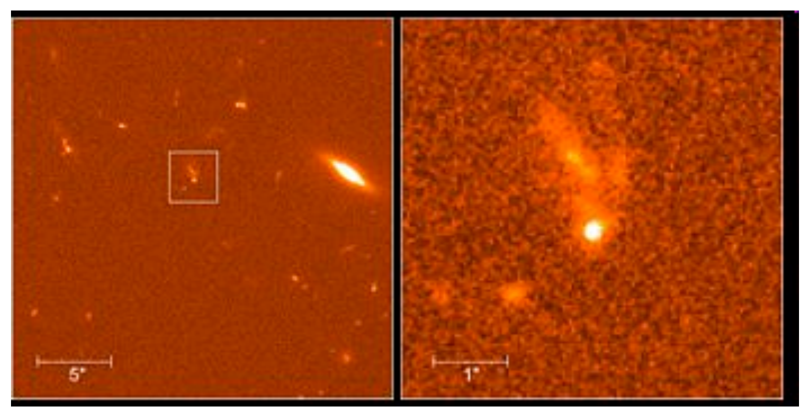
Has LIGO detected a gravitational wave yet?

- No, not yet.
- When will LIGO detect a gravitational wave?
- "Predictions are difficult, especially about the future"
  (Yogi Berra)
- Nonetheless…
  - » Enhanced LIGO
    - – 2009-2010
    - – Most probable event rate is 1 every few years for NS/NS inspirals
  - » Advanced LIGO
    - – 2015-beyond
    - – Rates are much better
- In the meantime, we set upper limits on rates from various sources

Gamma Ray Bursts

- Intense flashes of gamma rays from (mostly) extra-galactic sources
  - GRBs are the most luminous events in the Universe
- Long (> 2 s) and short duration (< 2 s)
  - Long GRBs are associated with star forming galaxies
    - Large red shift, Z=2.6
  - Short GRBs are less well understood
    - Soft gamma repeaters → magnatars





NASA Hubble Space Telescope Imaging Spectrograph (STIS)

Short Duration GRBs

Oct. 6, 2005

Fox, et al., Nature 437, 845 (2005)

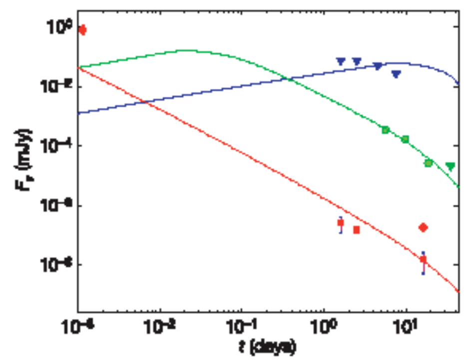


Figure 3 | **Observations of the GRB 050709 afterglow and illustrative models.** The X-ray (red), optical (green) and radio (blue) data taken from

Gehrels, et al., Nature 437, 851 (2005)

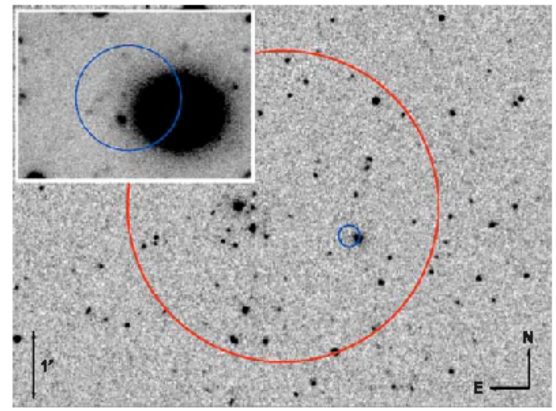


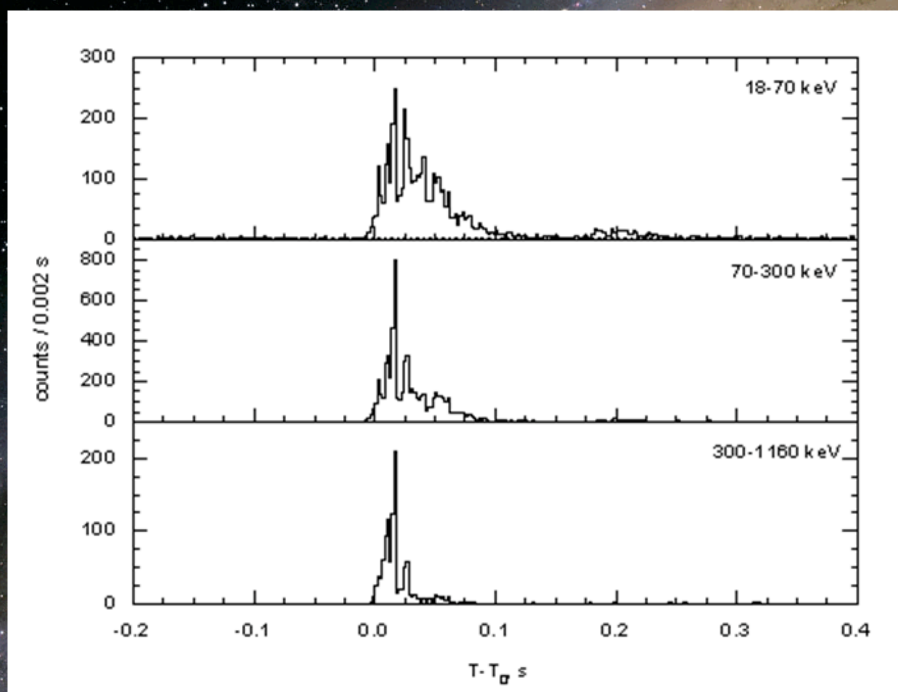
Figure 1 | **Optical images of the region of GRB 050509B showing the association with a large elliptical galaxy.** The Digitized Sky Survey image.

"There may be more than one origin of short GRBs, but this particular short event has a high probability of being unrelated to star formation and of being caused by a binary merger."

"In all respects, the emerging picture of SGB properties is consistent with an origin in the coalescence events of neutron star–neutron star or neutron star–black hole binary systems."

GRB 070201

Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3
"…The error box area is 0.325 sq. deg. The center of the box is 1.1 degrees from the center of M31, and includes its spiral arms. This lends support to the idea that this exceptionally intense burst may have originated in that galaxy (Perley and Bloom, GCN 6091)…" from GCN6013



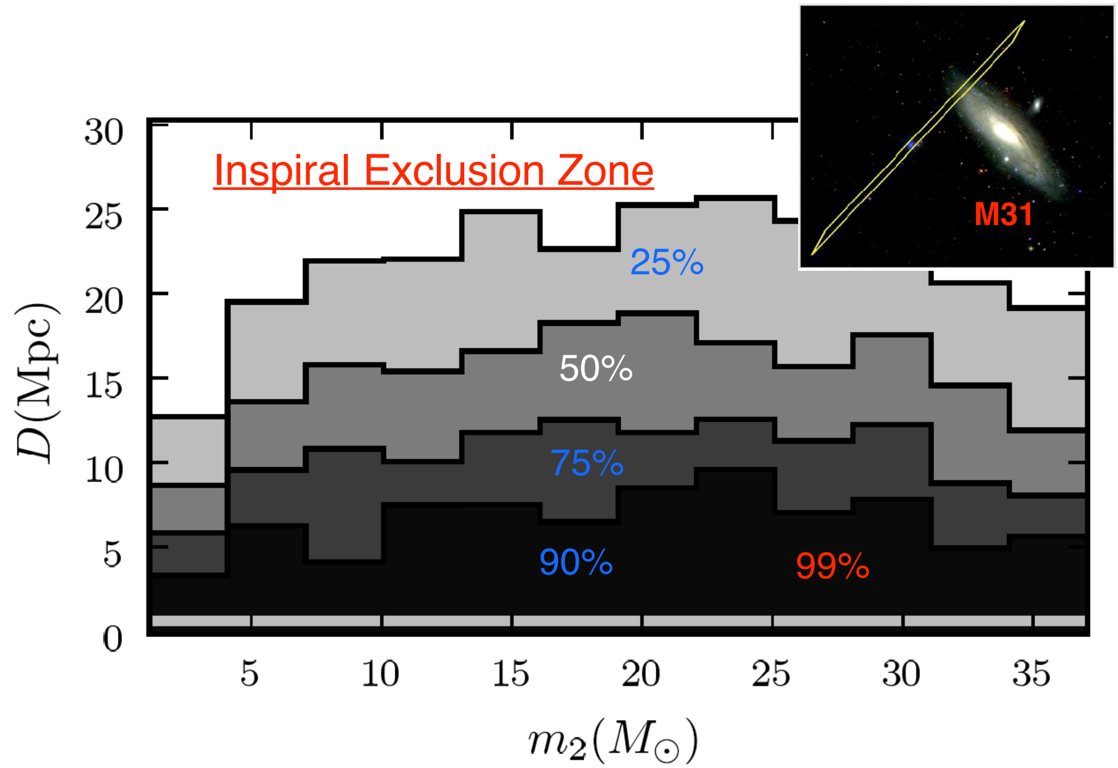
M31
The Andromeda Galaxy
by Matthew T. Russell
Date Taken:
10/22/2005 - 11/2/2005

Location:
Black Forest, CO

Equipment:
RCOS 16" Ritchey-Chretien
Bisque Paramoune ME
AstroDon Series I Filters
SBIG STL-11000M
http://gallery.rcopticalsystems.com/gallery/m31.jpg

Results - GRB070201

- Inspiral search:
  - Binary merger in M31 scenario excluded at >99% level
  - Exclusion of merger at larger distances

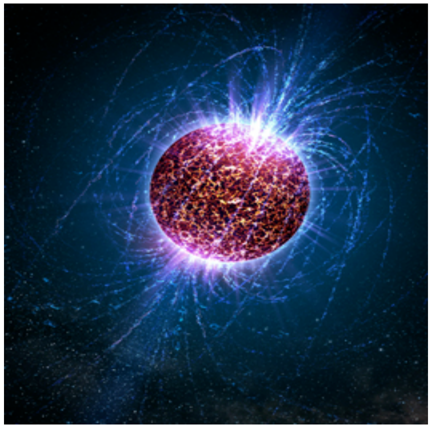


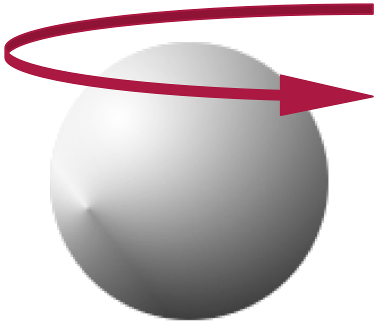
- Burst search:
  - Cannot exclude a SGR in M31 distance
  - Upper limit: 8×10^{50} ergs (4×10^{-4} $M_{\odot}c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)

Pulsars

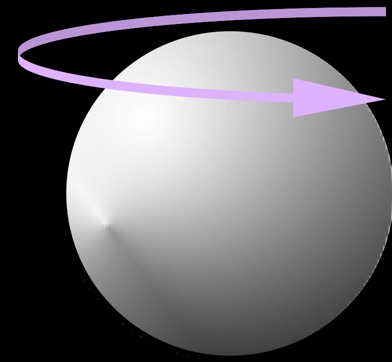
- Spinning neutron stars slow down due to:
  - Symmetric particle ejection
  - Magnetic dipole radiation
  - Gravitational wave emission
- Neutron stars could emit gravitational waves if:
  - They are non-axially distorted from crustal shear stresses
  - They have non-axisymmetric instabilities due to internal hydrodynamic modes
  - They wobble about their axis
- But the emission amplitude will be very small…

→ Upper limits on asymmetries in NS



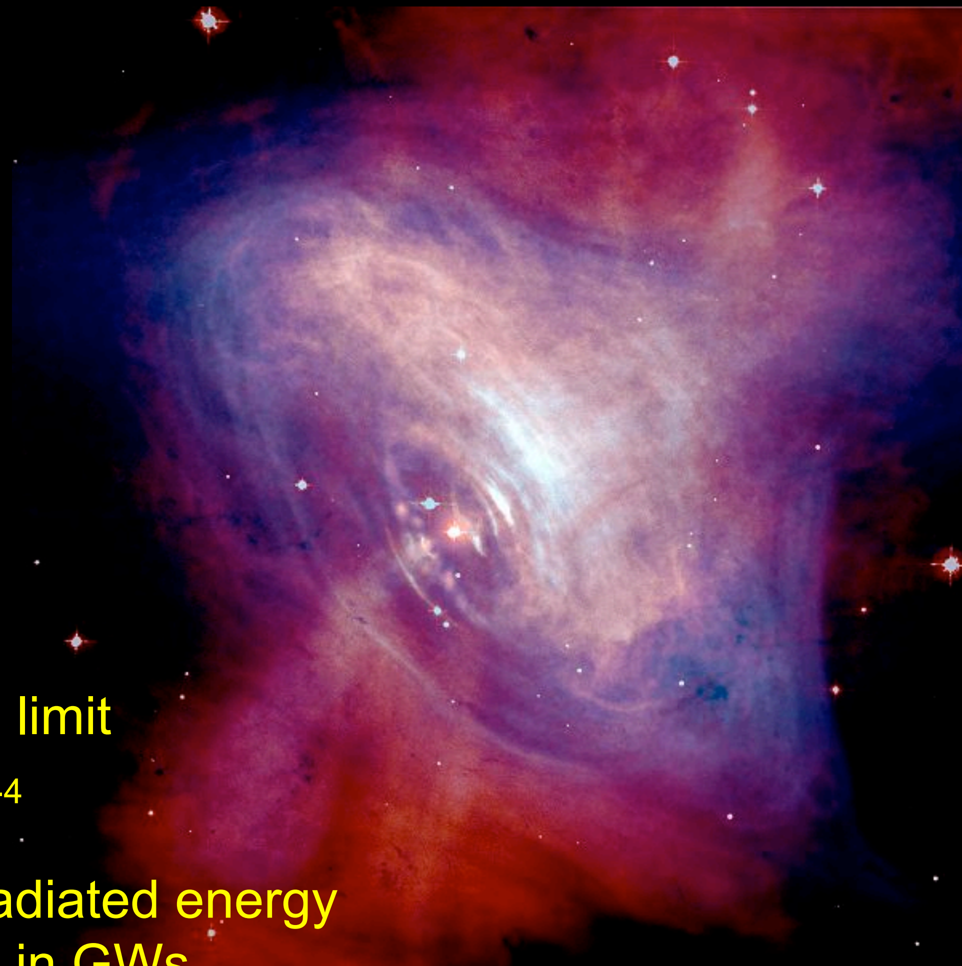


The Crab Pulsar



- Spinning neutron star
  - remnant from supernova in year 1054
- spin frequency ν_{EM} = 29.9 Hz

  → $\nu_{gw} = 2\,\nu_{EM}$ = 59.8 Hz
- spin down due to:
  - electromagnetic braking
  - *GW emission?*

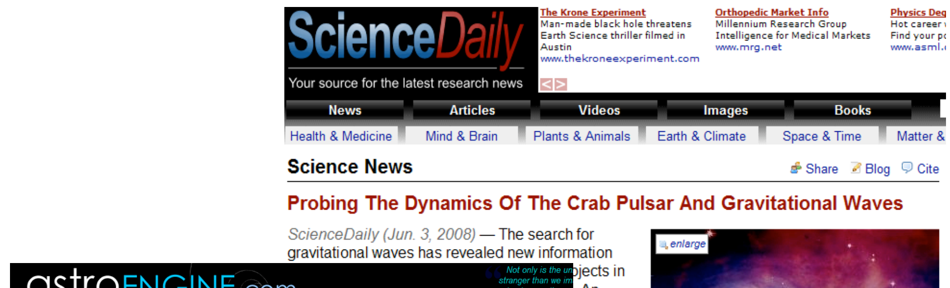


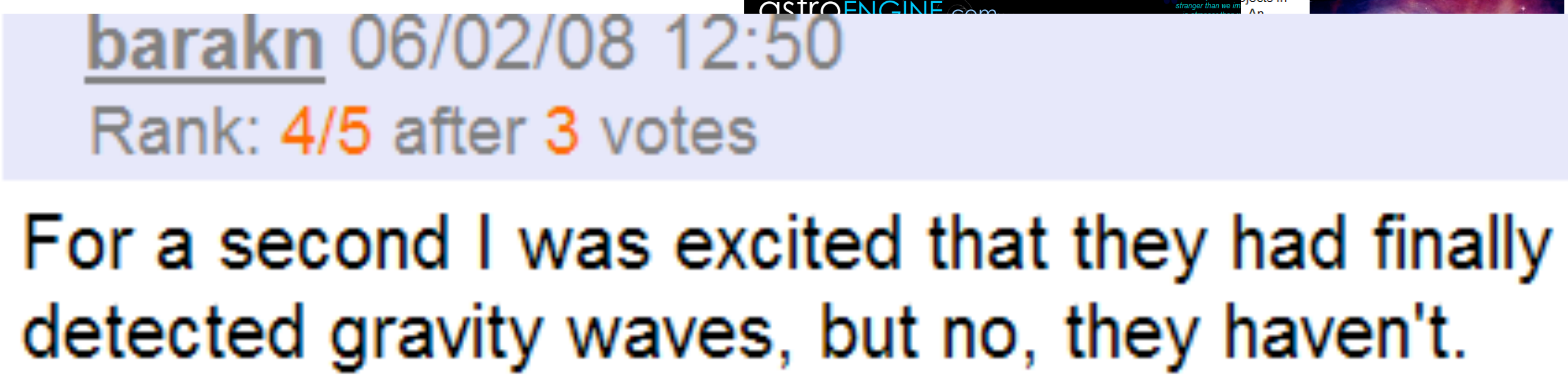
- GW strain upper limit:

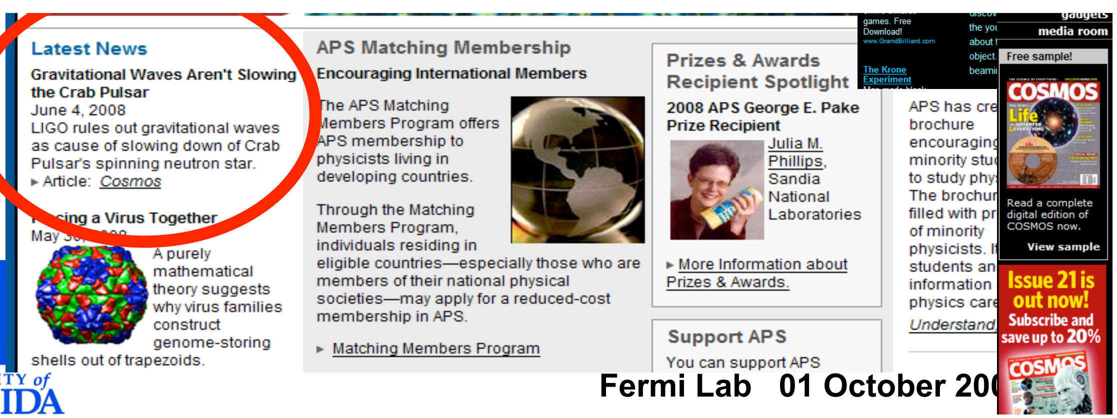
  $h < 2.7 \times 10^{-25}$ → 5.3 x *below* the spin down limit
- ellipticity upper limit: $\varepsilon < 1.8 \times 10^{-4}$
- GW energy upper limit < 4% of radiated energy is in GWs

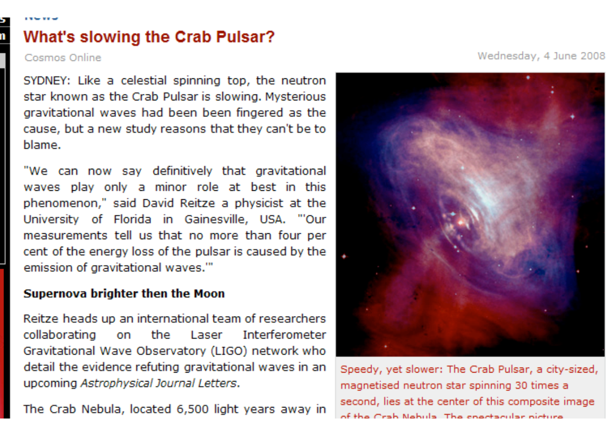
The Crab Pulsar Result

- Picked up by press, science web sites…
- … and bloggers!

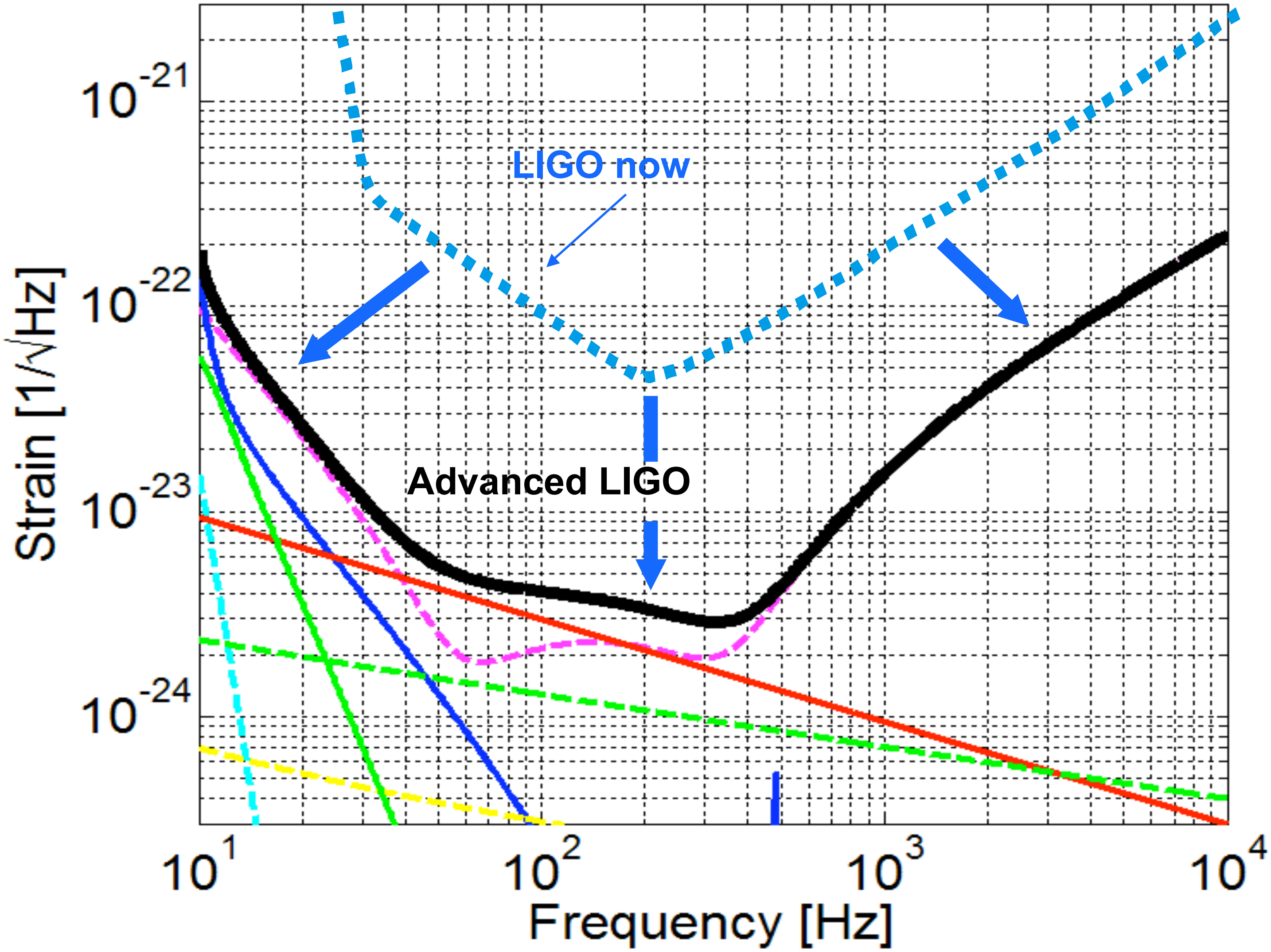




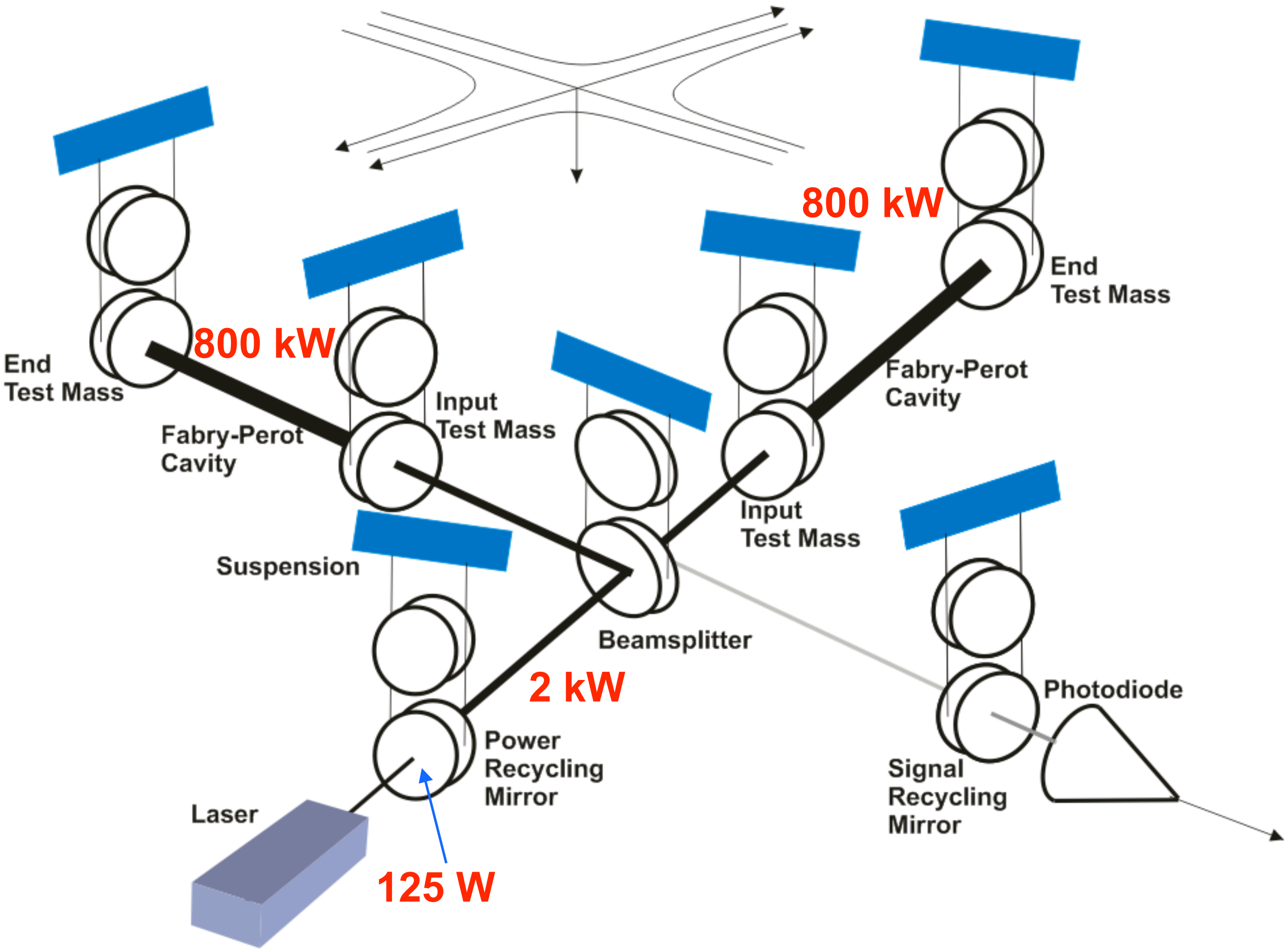




Advanced LIGO

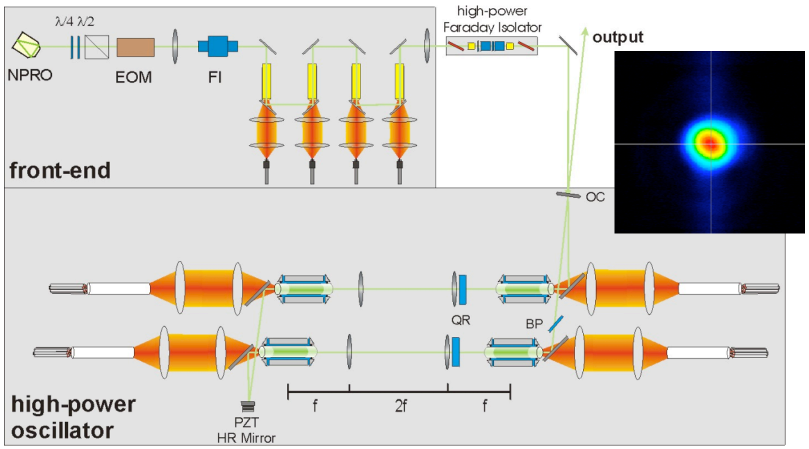


Advanced LIGO



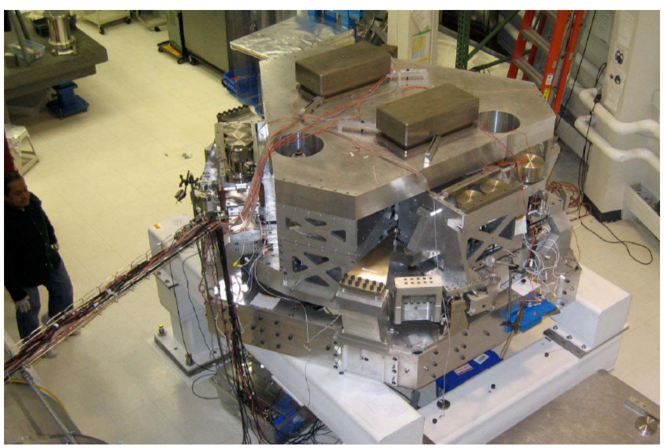
Advanced LIGO

180 W laser

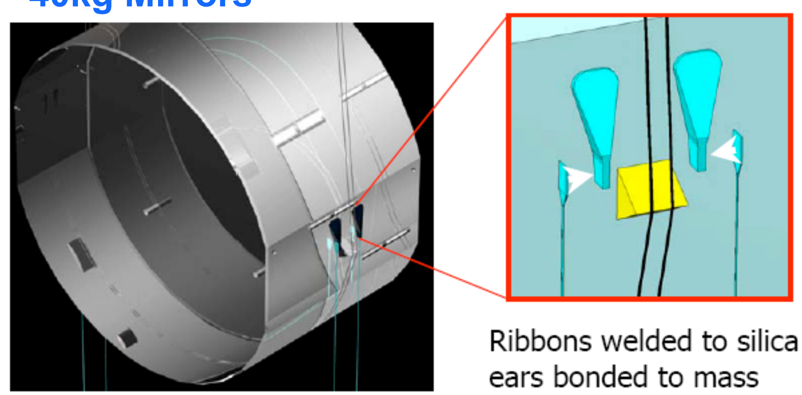


Mirror Suspensions

Seismic isolation



40kg Mirrors



Ribbons welded to silica ears bonded to mass

LIGO Scientific Collaboration

LIGO

LSC

MICHIGAN

UNIVERSITY OF STRATHCLYDE

ACIGA

UNIVERSITY OF MARYLAND 1856

MONTANA STATE UNIVERSITY

LOYOLA UNIVERSITY NEW ORLEANS

SOUTHERN UNIVERSITY Agricultural & Mechanical College

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

Università degli Studi del Sannio

San José State UNIVERSITY

UNIVERSITY of WISCONSIN UWMILWAUKEE

SYRACUSE UNIVERSITY FOUNDED AD 1870

UNIVERSITY of GLASGOW

TRINITY UNIVERSITY

UNIVERSITY OF ROCHESTER

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

NAOJ

LSU

UTB TSC

Science & Technology Facilities Council Rutherford Appleton Laboratory

1754

NASA GODDARD SPACE FLIGHT CENTER

Andrews University

Moscow State University

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

NORTHWESTERN UNIVERSITY

THE UNIVERSITY OF TEXAS AT AUSTIN

THE UNIVERSITY OF ADELAIDE AUSTRALIA

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SOUTHEASTERN LOUISIANA UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA

HOBART AND WILLIAM SMITH COLLEGES

PAN

PENNSTATE 1855

CARLETON COLLEGE

GEO 600

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

CARDIFF UNIVERSITY

UIB Universitat de les Illes Balears

WASHINGTON STATE UNIVERSITY

University of Southampton

UNIVERSITY OF MINNESOTA

The University of Mississippi

CHARLES STURT UNIVERSITY

Universität Hannover

UF UNIVERSITY of FLORIDA

Acknowledgments

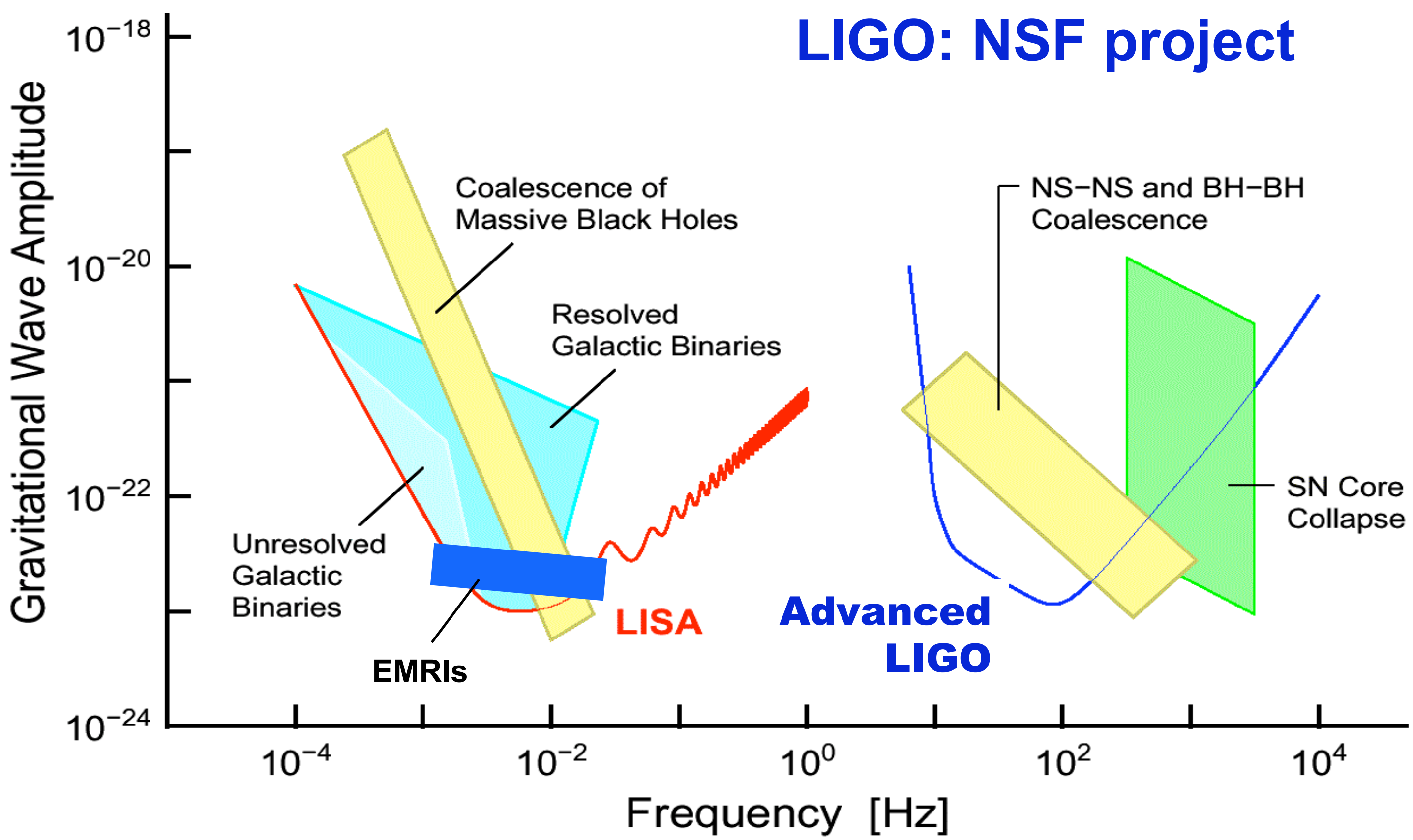
- Members of the UF LIGO group
- Members of the LIGO Laboratory
- Members of the LIGO Science Collaboration
- National Science Foundation

More Information

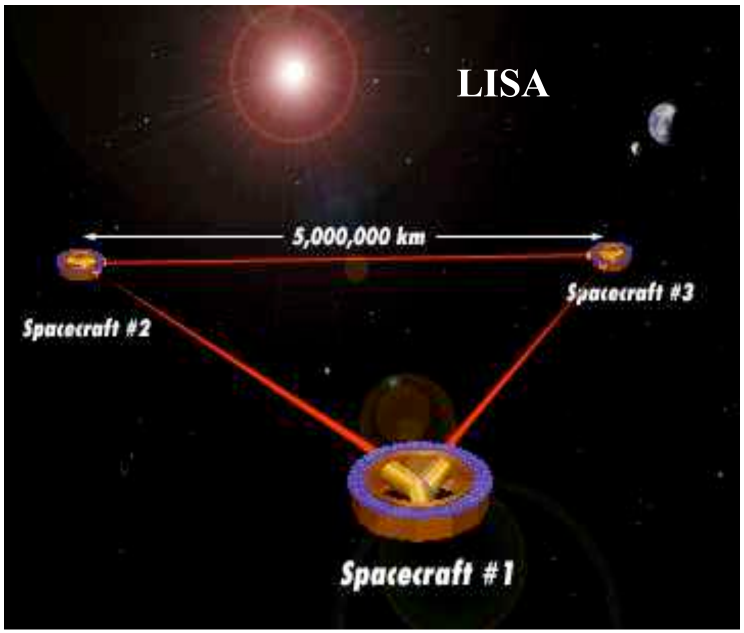
- http://www.ligo.caltech.edu; www.ligo.org

LIGO & LISA

LISA: Joint NASA/ESA project



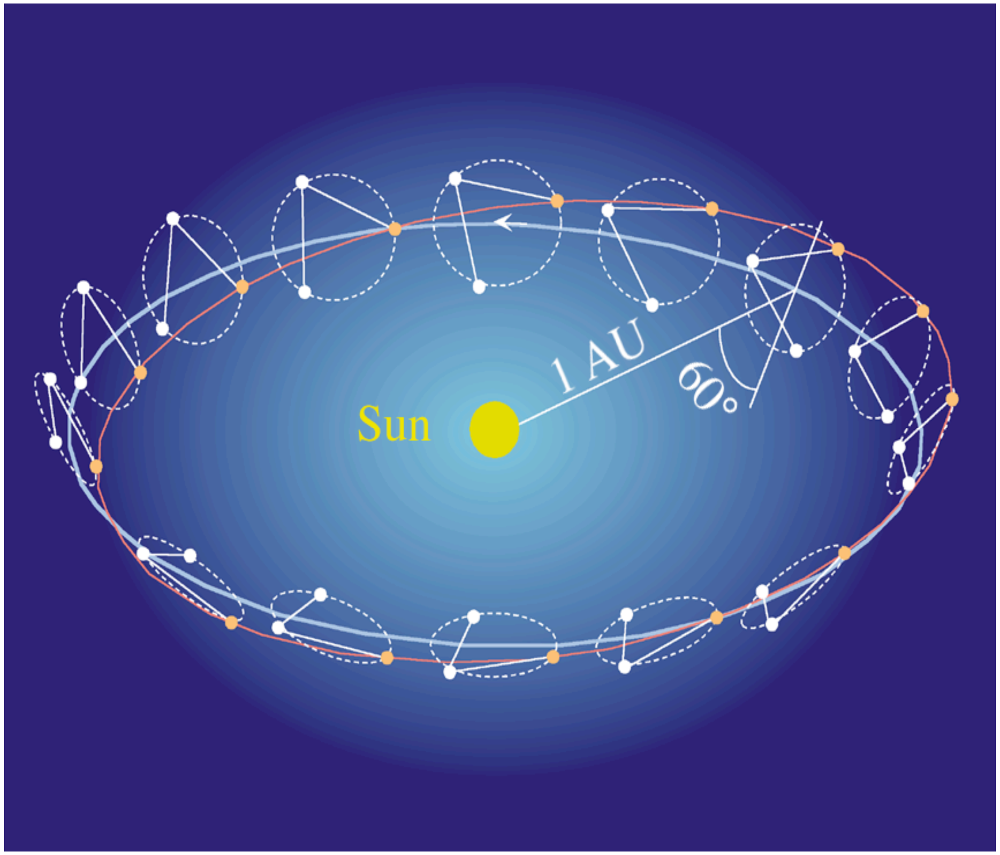
The Mission



- 3 spacecraft constellation
- S/C separated by 5×10^6km
- Drag-free proof masses inside each S/C
- Earth-trailing solar orbit
- 5 year mission life
- pm-Sensitivity

Orbits

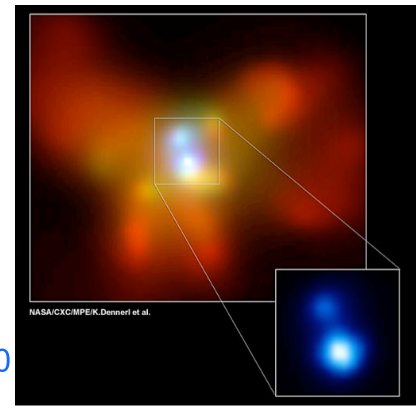
- Orbits are chosen so that the spacecraft passively hold formation.
- Spacecraft have constant solar illumination and benign environment.



LISA Sources

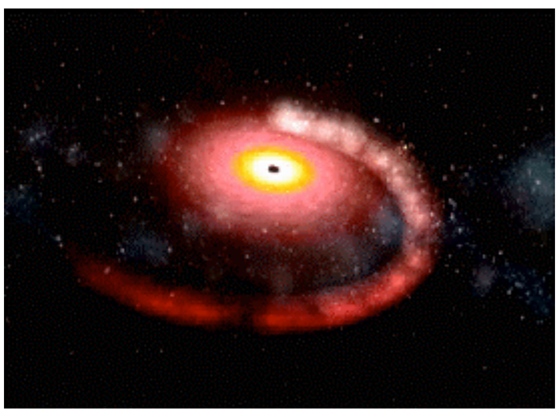
Guaranteed signals!

1. **Super-massive Black Hole mergers**

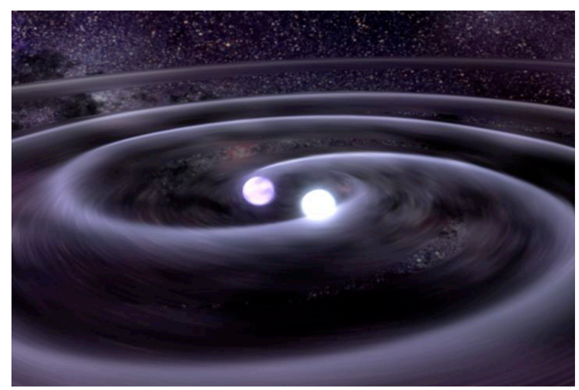


Chandra: NGC6240

2. **Extreme mass ratio Inpirals (EMRIs)**



3. **Galactic Binaries long before they merge**

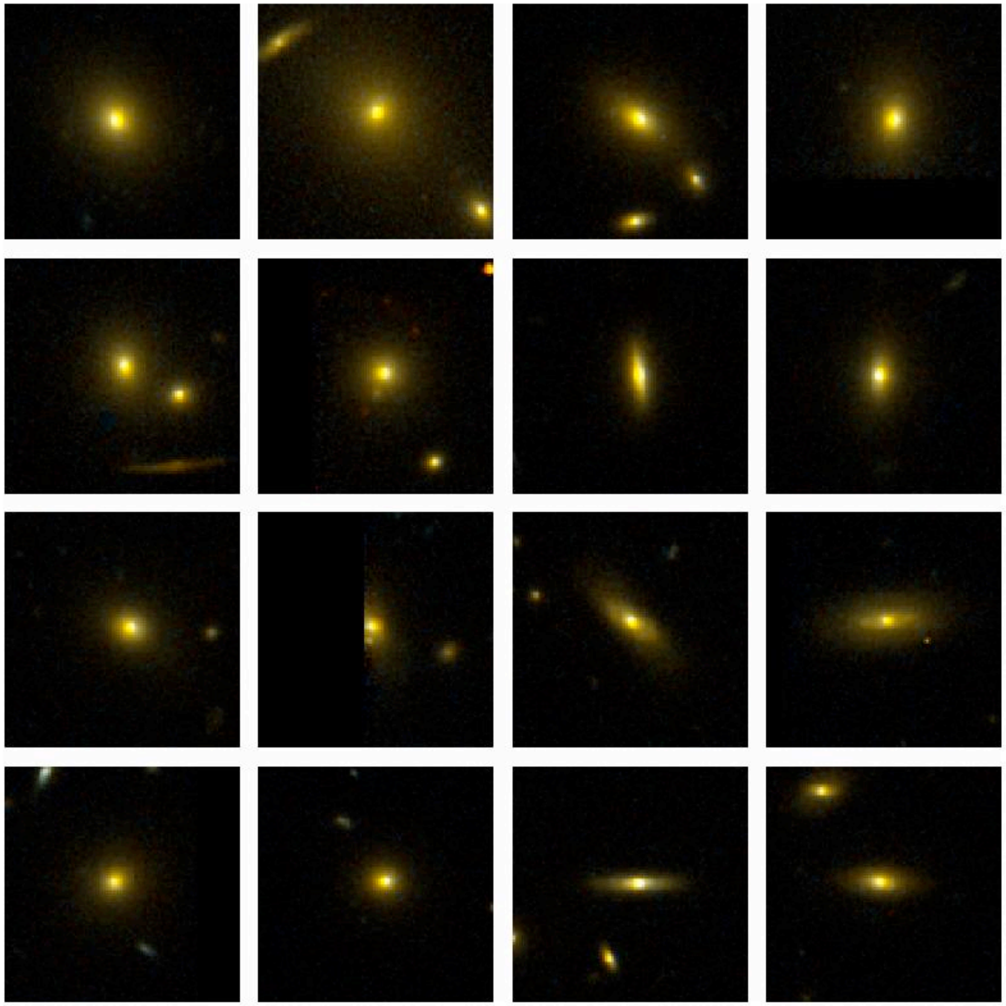


Credit: Tod Strohmayer (GSFC)

SMBH merger rates

What do we know?

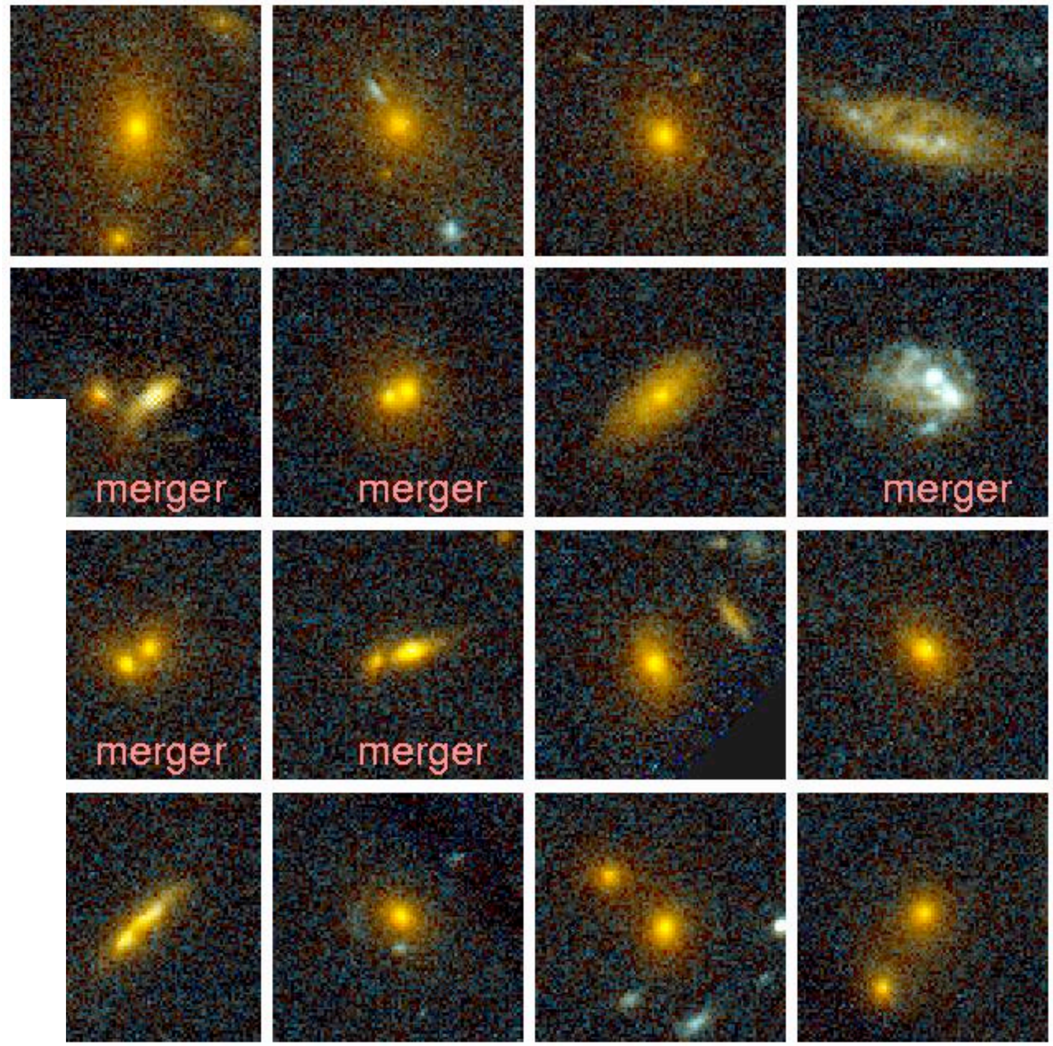
- **Almost all galaxies host a massive black hole. But do they merge?**
- **Essentially no mergers seen in cluster MS 1358-62 (z = 0.32)**
- **Shown: 16 brightest galaxies. No apparent mergers!**



SMBH merger rates

What do we know?

- Almost all galaxies host a massive black hole. But do they merge?
  - Mergers in rich cluster MS 1054-03 (z = 0.83)
  - Shown: 16 brightest galaxies. About 20% are merging!



van Dokkum et al 1999, ApJ 520,L95.

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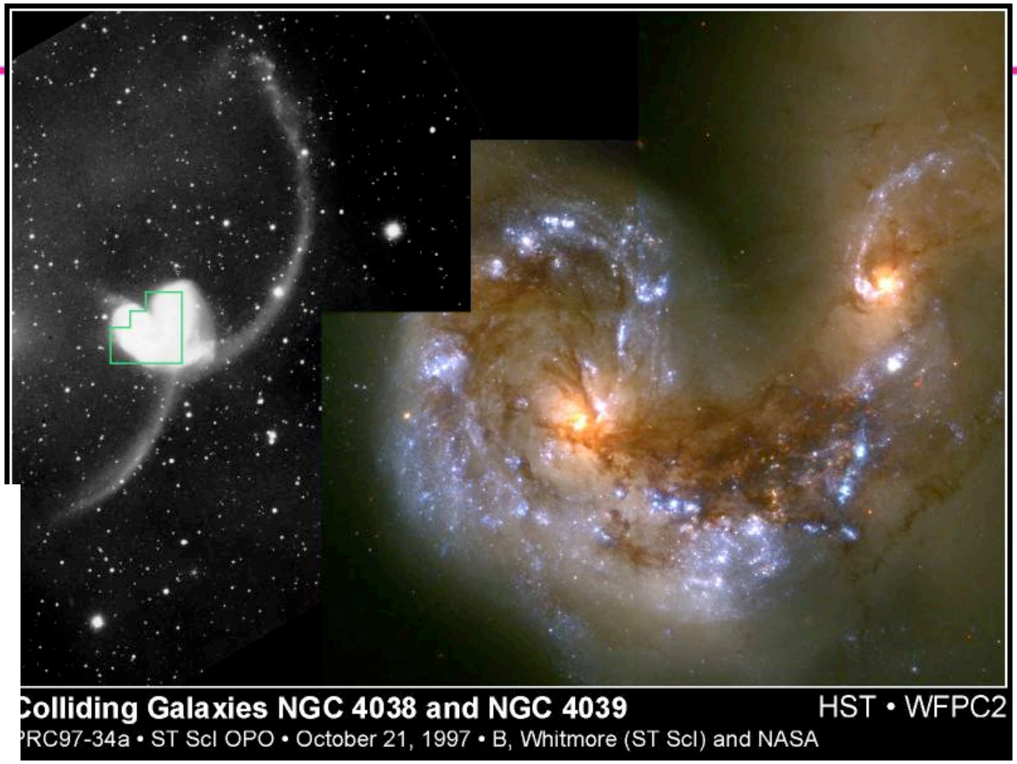
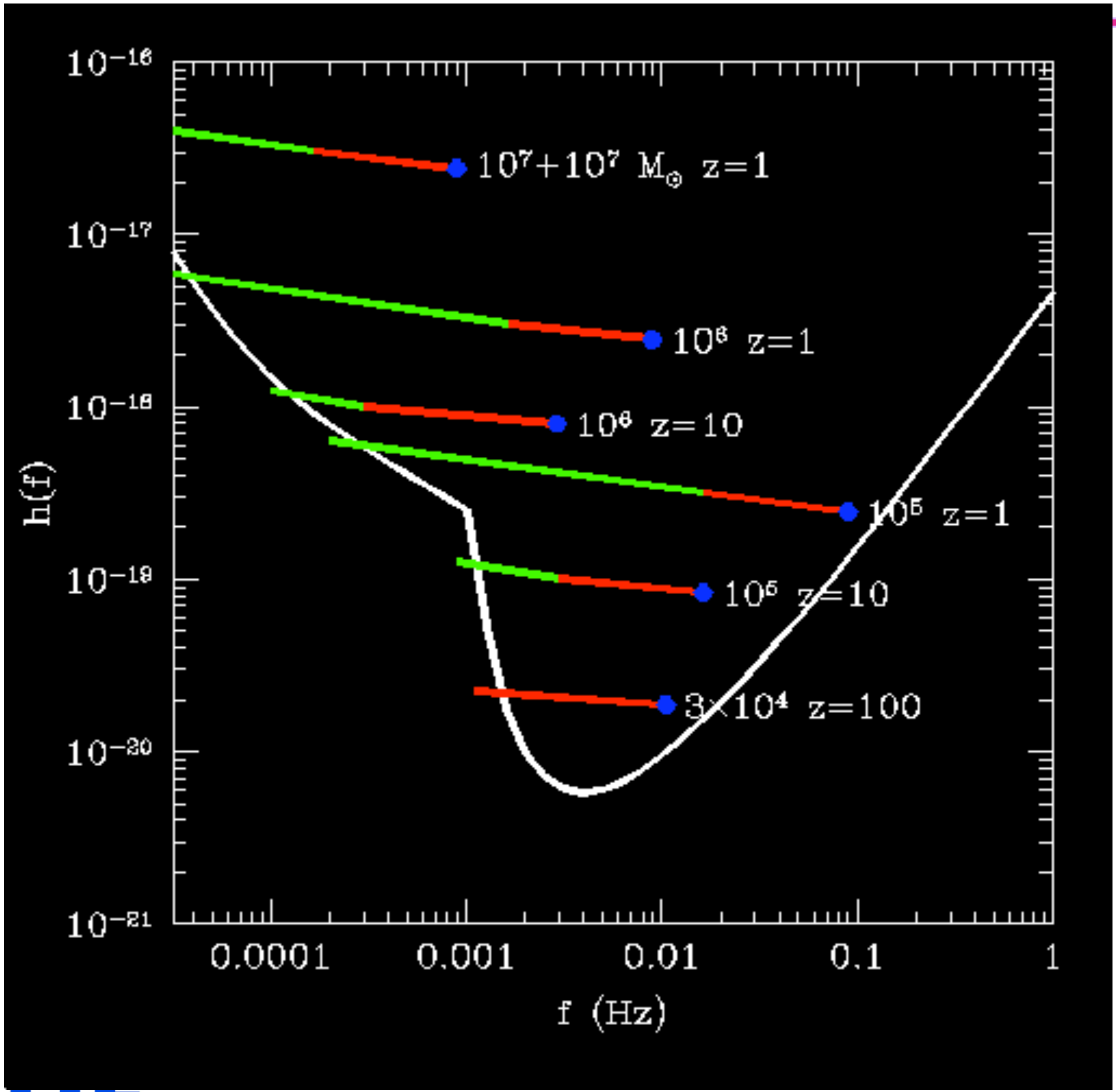


Event rate: At least a few events per year!

(almost certain)

(Haehnelt 1994; Menou, Haiman, & Narayanan 2001; Wyithe & Loeb 2003; Islam, Taylor, & Silk 2004; Sesana et al 2004)

SMBH Mergers



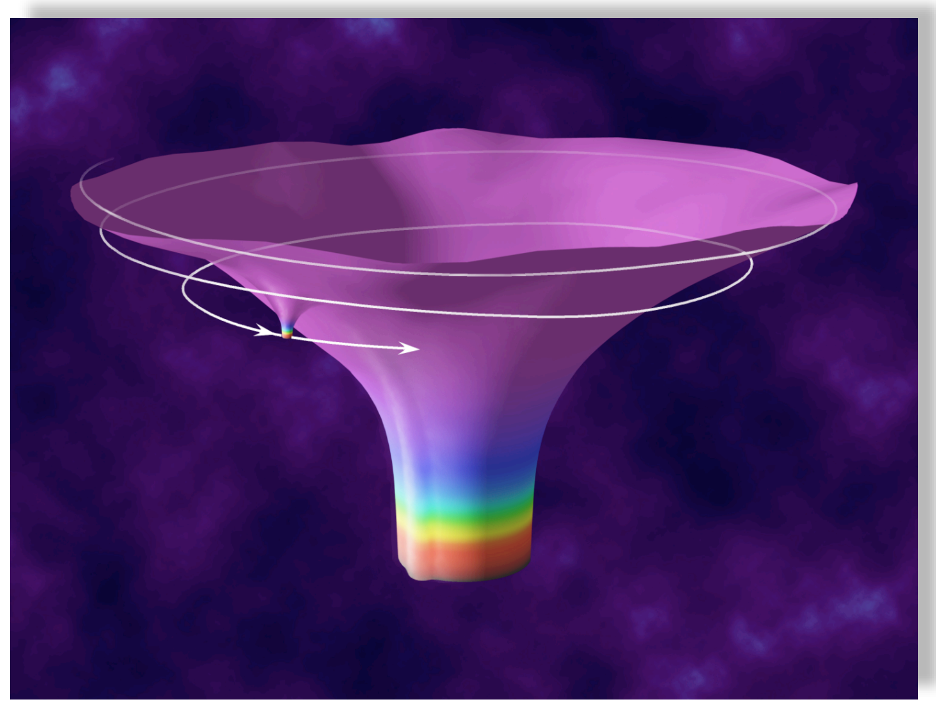
- Mass/Redshift range:
  $10^5 M_{sun} < (1+z)M < 10^7 M_{sun}$
  out to z~10
- Start to show up at low frequencies months before merging.
- Predict merger weeks in advance.
- The "dream comes true" event: Parallel Observations with Hubble, Chandra, and other EM-telescopes.
- Allows measurement of 'Dark Energy'

EMRI

EMRI: Extreme Mass
Ratio Inspiral

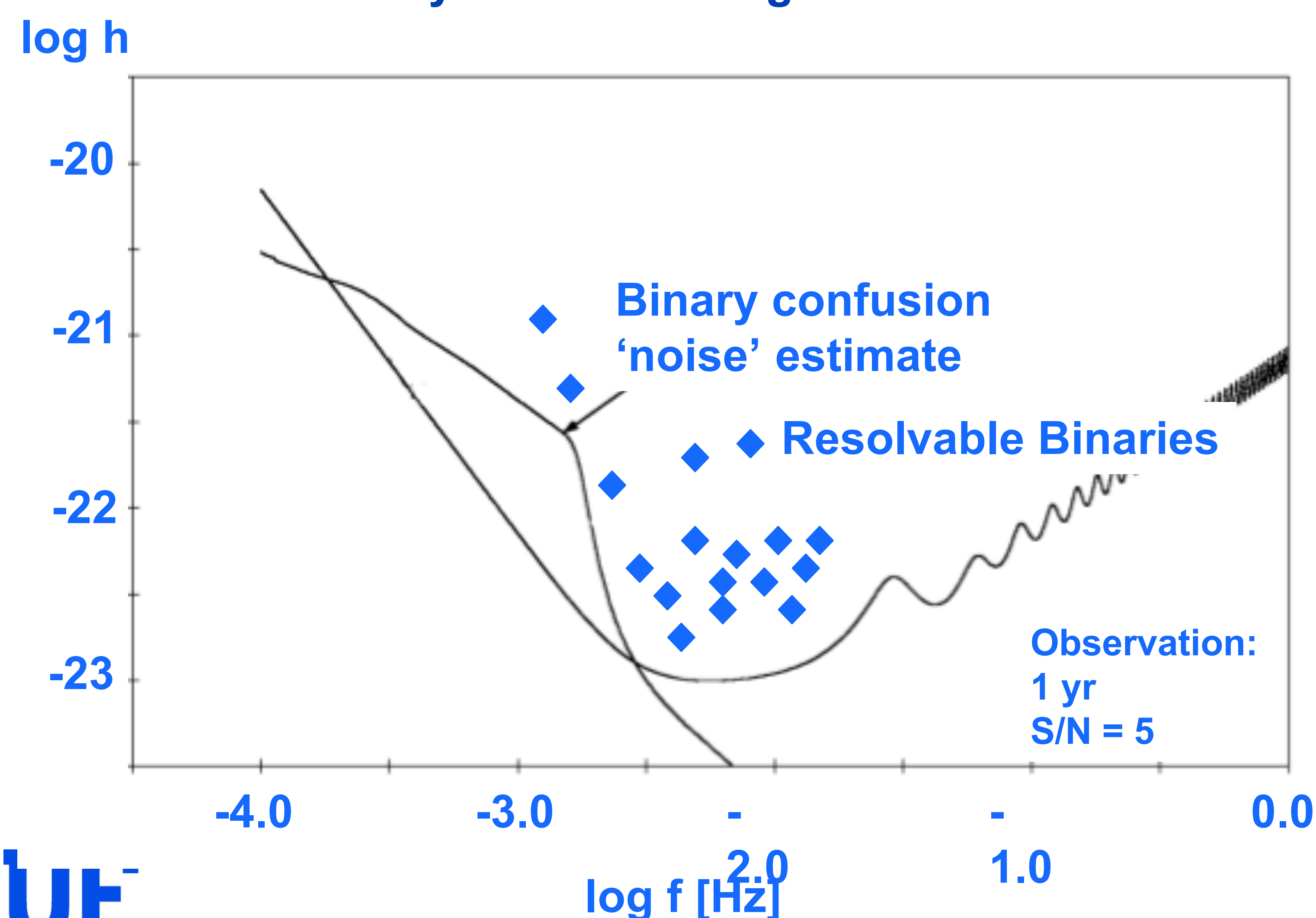
1-100 M_S falls into $10^8 M_S$

- LISA Core Target
- Test particle case for gravitational waves



Galactic Binaries

Binary Confusion 'Signal' or 'Noise'



- Noise, if you are interested in SMBH or EMRIs
- Signal, if you are interested in Galactic Binary populations

What others say about LISA

AANM (2001)

"LISA is unique among the recommended new initiatives in that it is designed to detect the gravitational radiation predicted by Einstein's theory of general relativity. The direct measurement of gravitational radiation from astrophysical sources *will open a new window onto the universe* and enable investigations of the physics of strong gravitational fields."

Q2C (2003)

LISA and Con-x have "*great potential to address questions that lie at the boundary between physics and astronomy*."

Beyond Einstein (BE) Roadmap (2003)

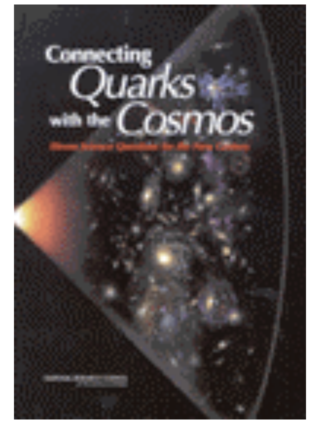
"The cornerstones of the program are two Einstein Great Observatories, Con-X and LISA."

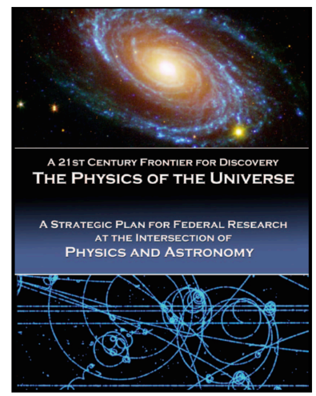
Physics of the Universe (NSTC/OSTP - 2004)

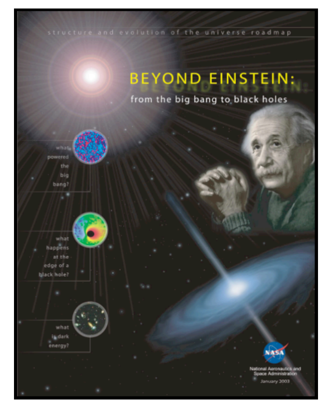
The execution of the LISA mission is "*necessary to open up this powerful new window on the universe* and create the new field of gravitational wave astronomy."

"Mid-course" Review of Decadal Study (CAA-2005)

LISA and Con-X "*will provide a broad and flexible science return across all of astrophysics* as have HST, CGRO, Chandra and Spitzer".







BEPAC

Beyond Einstein Program Assessment Committee (BEPAC) was asked by NASA and DOE to:

Assess the five proposed Beyond Einstein missions and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY2009.

"LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways. LISA, in the committee's view, should be the flagship mission of a long-term program addressing Beyond Einstein goals."

"On purely scientific grounds LISA is the (Beyond Einstein) mission that is most promising and least scientifically risky. Even with pessimistic assumptions about event rates, it should provide unambiguous and clean tests of the theory of general relativity in the strong field dynamical regime and be able to make detailed maps of space time near black holes. Thus, the committee gave LISA its highest scientific ranking."

LISA Status

My personal view:

LISA is currently waiting on

- **LISA Pathfinder: A mission to test the gravitational reference sensor which will be launched end of 2011.**
- **The next Decadal survey**
- **The first detection by LIGO**

The Universe in GW